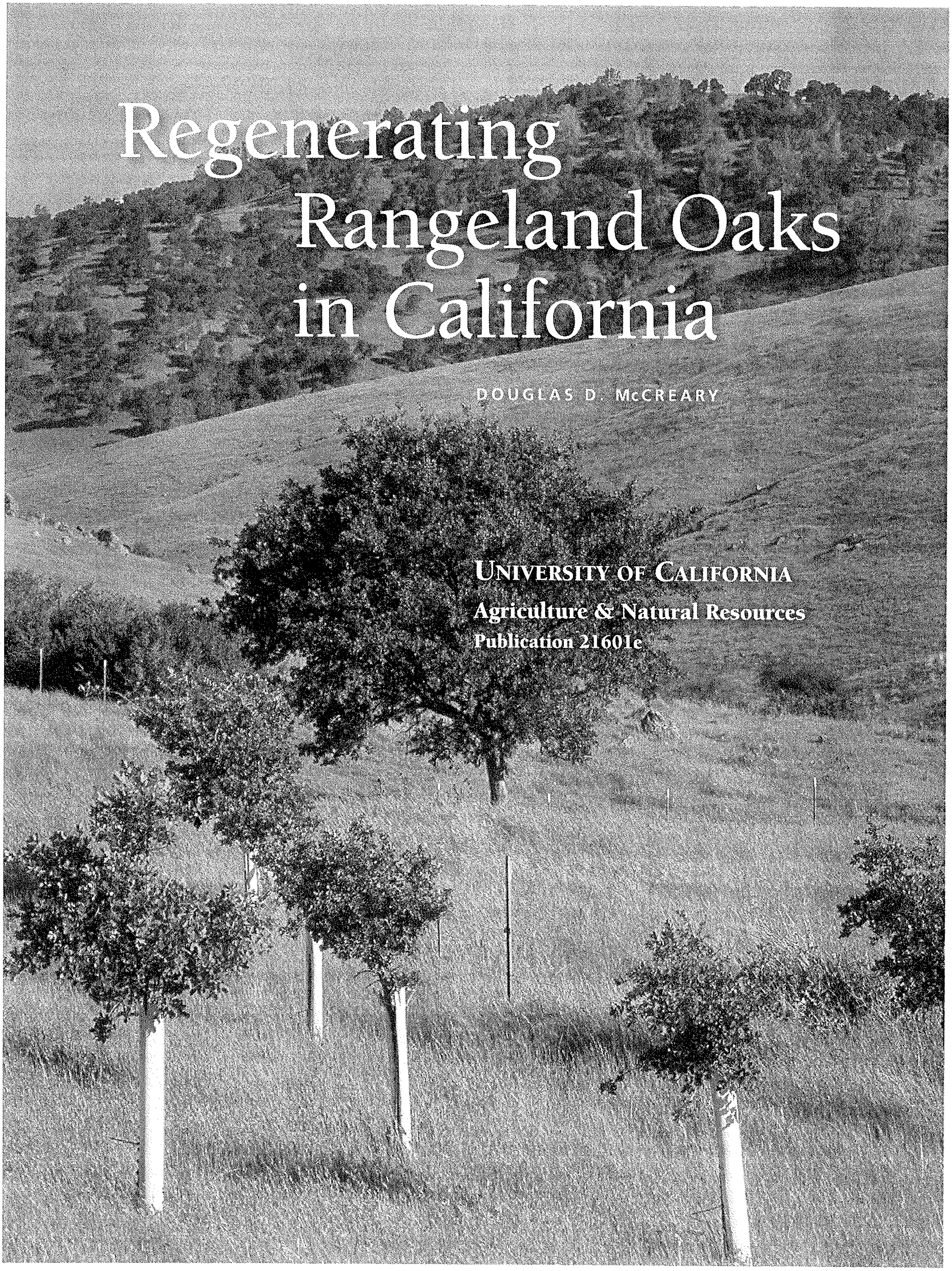
Appendix D
Examples of Oak Woodland Restoration Research

Regenerating Rangeland Oaks in California

DOUGLAS D. McCREARY



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Regenerating Rangeland Oaks in California

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Contents

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Introduction

For millennia, oaks have graced the valleys, hills, and mountains of California. The state has a rich and diverse assortment of *Quercus* species, which range in appearance from majestic solitary valley oaks (*Quercus lobata* Nee), with enormous trunks and massive canopies, to small, shrublike, huckleberry oaks (*Quercus vaccinifolia* Kellogg) that never grow more than a few feet tall. For many residents and nonresidents alike, golden-brown hills dotted with gnarled oak trees epitomize the California landscape, and native oaks symbolize values we hold dear—strength, beauty, adaptability, and longevity. The deep and endearing value of oaks in the psyche of the early settlers is clearly seen by a glimpse at any state map, where so many city and landmark names include *oak* or the Spanish equivalents *encina* and *roble*. To California's native peoples, oaks were even more revered and figured prominently in their world view and spiritual beliefs. Among other things, oaks were the source of *acorn*, a staple food source of many tribes.

The value of oaks goes well beyond their stature and beauty and how people view them. Oaks and oak woodlands are home to a rich and diverse assortment of wildlife. More than half of the 662 species of terrestrial vertebrates in California utilize oak woodlands at some time during the year, and the food and shelter provided are essential to their survival. Oaks are also critical in protecting watersheds and ensuring the quality of water resources. The majority of the state's water is stored as snowpack in high-elevation mountains before flowing through oak woodlands in rivers that support fisheries, farms, and cities. Oak trees anchor the soil, preventing erosion and sedimentation.

But not all is well with California's oaks and oak woodlands. In addition to adverse impacts from firewood harvesting, agricultural conversions, intensive grazing, and residential and commercial development, there has been concern for a number of years that several oak species are not regenerating well in portions of the state. These species grow primarily in the foothills of the Sierra, Coastal, and Transverse mountain ranges, regions that are commonly referred to as hardwood rangelands. As a result of concern about poor regeneration, there has been a concerted effort to develop successful techniques for the artificial regeneration of the rangeland oak species. Research has addressed a wide array of subjects, including acorn collection, storage, and handling; seedling propagation methods; and techniques for planting, protecting, and maintaining seedlings in the field. There has been a great deal of research on this subject in the last decade, and we have come a long way in understanding how to grow and plant rangeland oaks. Nevertheless, the results of this research have been largely fragmented and dispersed in a wide range of documents, including homeowner brochures, internal reports, and scientific publications in rather obscure journals.

This manual attempts to bring together the information available on artificially regenerating rangeland oaks in California. The manual's primary purpose is to provide a resource for restorationists, hardwood rangeland managers, and others involved in oak propagation and planting projects so that their efforts are based on the latest scientific information available and are, ultimately, more successful. I also hope that this document will be of interest to others not directly involved in regenerating oaks but who maintain a deep, personal interest in the ecology and management of *Quercus* species.

Organization of this Manual

This manual is divided into four chapters. The first chapter deals with the subject of poor natural regeneration of native California oaks and identifies the oak species that appear to be regenerating poorly and the conditions under which this problem seems most acute. It also describes a number of theories that have been proposed to explain why regeneration appears to be less successful today than in the past.

The second chapter focuses on acorns and provides an overview of acorn physiology, as well as a discussion of the suspected causes for the large variability in the size of acorn crops from year to year. This chapter also describes how to collect and store acorns and the recommended procedures for sorting and testing them. There is a brief discussion of genetic variability and the importance of maintaining local seed sources. Finally, information is presented on how, when, and where to sow acorns and the pros and cons of directly planting acorns in the field versus planting seedlings that have been raised in nurseries.

The third chapter discusses oak seedling propagation. Some of the more common methods of growing seedlings are presented, including case studies of three nurseries that have been producing California oaks in containers for well over a decade. The possibility of vegetatively propagating oaks is also discussed, as are the potential benefits of inoculating oak seedlings with mycorrhizae. This chapter is designed to provide a broad overview of production techniques; readers contemplating growing oaks on any large scale are advised to obtain further information from other sources, including those nurseries listed in the appendixes.

The fourth and longest chapter addresses the general subject of planting, protecting, and maintaining oak seedlings in the field. This encompasses how to select planting sites and actually plant seedlings, as well as how to overcome the two main obstacles to successfully establishing oaks: controlling competing vegetation and preventing damage to acorns and young plants by animals. A considerable amount of discussion is devoted to treeshelters since studies at the University of California Sierra Foothill Research and Extension Center (SFREC) show that these devices are particularly useful for artificially regenerating oaks, both in terms of stimulating seedling growth and preventing damage from a wide range of animals. This chapter concludes with a discussion of other practices that may enhance regeneration success, including augering planting holes, fertilizing, irrigating and shading seedlings, and top pruning.

Each of the last three chapters also contains side bars that are intended to summarize the important points covered and provide practical guides for artificially regenerating California's rangeland oaks. Following a brief conclusion are the appendixes, which are included to provide additional resources and information to assist in better understanding oak regeneration and embarking on programs to grow or plant oaks.

Finally, there is a list of all of the references cited in this manual. The main focus of the references has been to identify research conducted in California on native oak species, and most specifically, on blue oak (*Quercus douglasii* Hook. & Arn.) and valley oak. In several instances, however, relevant research from other parts of the United States and the world is also identified. It is important to point out here that the problem of poor oak regeneration, and efforts to overcome it, is not unique to California. Concerns about oak management in the Middle Ages led to forest ordinances in France—including planting programs—designed to ensure the establishment of oaks. And in the Eastern United States, concerns about oak regeneration go back to the early 1800s. There is, therefore, a large amount of literature and information on this general subject from outside of California. For those who are interested, several general references about oaks and oak regeneration both inside and outside of California are listed in the bibliography, including conference proceedings, books, and software. These references provide readers with a starting point for delving deeper into topics of interest.

It is also important to mention here that, while this manual attempts to be comprehensive and include information from throughout the state, and even from other parts of the world, much of it is based on research conducted over the past 12 years at the University of California Sierra Foothill Research and Extension Center (SFREC), located 15 miles northeast of Marysville, California. I have been very fortunate to be housed at the SFREC and, since it is located in a fairly typical oak woodland, it has proved an ideal location to carry out oak regeneration research. However, while the SFREC is representative of large areas of oak woodlands in the state, it is clearly unlike many other places where oaks grow. Consequently, the results and recommendations contained within this manual should certainly be applied to other situations cautiously. The principal characteristics of the SFREC are listed in table 1. As can be seen, the average annual rainfall is 28 inches (71 cm), which is considerably more than many areas farther south. Supplemental irrigation was not necessary in the studies described, but this may not be the case in areas of lower rainfall. Also, we report on results of trials where we have planted oaks in pastures grazed by cattle. Again, our planting areas are only moderately grazed, and in places where grazing intensity is greater, some of the procedures we recommend may be much less effective.

In spite of these limitations, it is hoped that this manual will be helpful and will, ultimately, promote the long-term conservation of oaks in California. That is the basic goal of the University of California Integrated Hardwood Range Management Program, as well as the goal of all our oak regeneration research and of this document.

Table 1. Characteristics of the University of California Sierra Foothill Research and Extension Center

Location	15 miles (24 km) northeast of Marysville, California, in rolling to steep foothills
Elevation	220–2,020 ft (67–616 m); most oak regeneration research plots are at approximately 600 ft (183 m)
Primary vegetation	oak woodlands and annual grass rangelands; primary woody species: blue oak, interior live oak (*Quercus wislizeni* A. DC.), valley oak, foothill pine (*Pinus sabiniana*)
Soils	generally rocky clay loams; primary series: Auburn, Argonaut, Las Posas, Wyman, Sobrante
Climate	Mediterranean climate zone with hot, dry summers and mild, rainy winters
Average annual rainfall	28 in (71 cm); range: 9–44 in (23–112 cm)
Temperatures	average year-round: 60°F (16°C); summer maximum mean: 90°F (32°C); winter monthly minimum: 40°F (4°C)
Historical use	cattle grazing

1

The Natural Regeneration of California Oaks

Since the turn of the century, there have been reports that certain species of hardwoods in California, including oaks, were not regenerating adequately (Jepson 1910). More recent assessments have also reported that several oak species do not seem to have sufficient recruitment to sustain populations. Describing the oaks in the foothill woodland of Carmel Valley, White (1966) stated that "a prevailing characteristic…is the lack of reproduction…with very few seedlings." Bartolome, Muick, and McClaran (1987) also concluded that "current establishment [throughout California] appears insufficient to maintain current stand structure for some sites." And Swiecki and Bernhardt (1998) reported that, at 13 of 15 blue oak locations evaluated throughout the state, "…sapling recruitment is inadequate to offset recent losses in blue oak density and canopy cover."

These regeneration assessments have relied on inventories of the size-class distribution of oaks, generally classifying the plants into three broad categories: seedlings, saplings, and mature trees. While the definitions of these classes have varied, there has been a consistent trend of finding fewer saplings or intermediate-sized trees than seedlings or mature trees (fig. 1). For instance, Phillips et al. (1997) assessed numbers of four size classes of blue oaks in different rainfall zones and reported fewer sapling- and pole-sized trees than seedlings or mature trees in all rainfall zones. It is important to note, however, that the trend of poor regeneration has only been observed in 4 of California's 22 native oak species, and patterns have varied greatly from place to place.

For these species, a general pattern of inadequate sapling recruitment has emerged in some locations. Since saplings are the trees that must be recruited into the mature size class when the older trees die, there is worry that, if these trends continue, current population densities will decline. Some areas that have historically been oak woodlands may therefore convert to other vegetation types, such as brushfields or grasslands. Generally, this regeneration problem is further exacerbated by land management practices that directly remove trees (firewood harvesting, clearing associated with construction, agricultural conversions, etc.), as well as by activities, such as intensive year-round grazing, heavy vehicle use, or yearly burning, that may create conditions in which it is much more difficult for oak seedlings to become established or grow.

However, not all assessments of existing oak stand structures have concluded that oaks are declining.

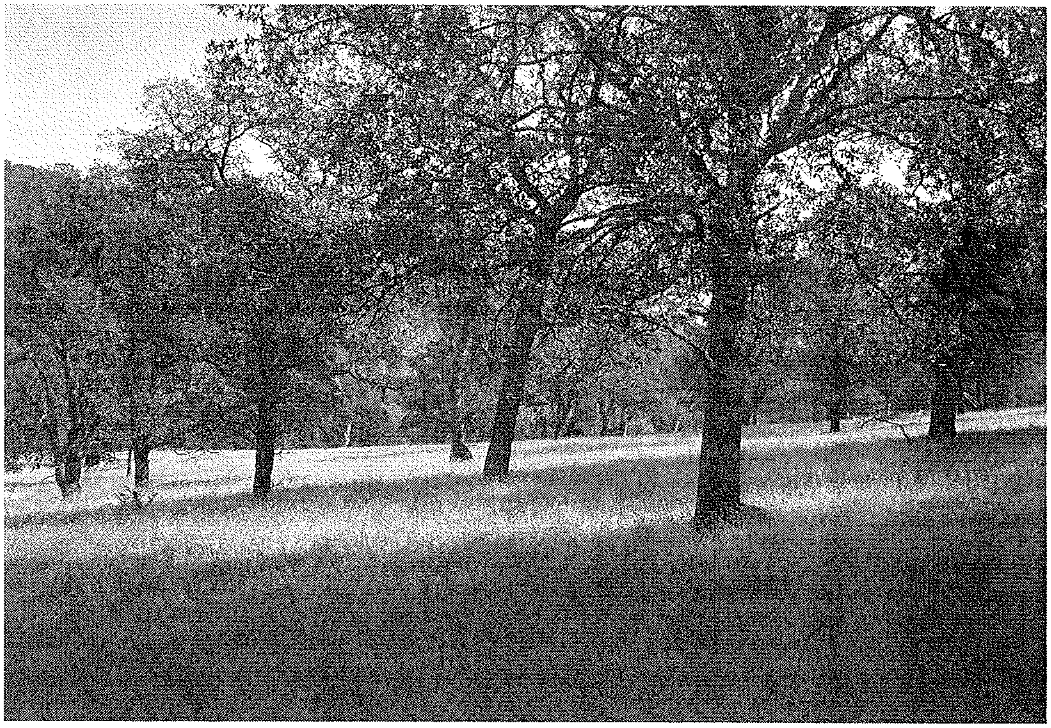

Figure 1. This mature oak stand at the SFREC has few oak saplings.

Holtzman and Allen-Diaz (1991) conducted a study that revisited vegetation plots charted in the 1920s and 1930s as part of a statewide effort to map vegetation (Wieslander 1935). They found that, in most plots originally containing blue oaks, there was an increase in the basal area of blue oaks, as well as an increase in the number of trees present. There was a decrease in the largest size class of trees, but this was offset by increases in other size classes. Davis, Brown, and Buyan (1995) also conducted an assessment of the cover and density of blue oak woodlands throughout the blue oak's current range to determine changes between 1940 and 1988. While they found many sites where woody cover had decreased, these were more than offset by sites where cover had increased. They concluded that there was little evidence of landscape-level or large-scale patterns of change. Both of these studies suggest that, in the time periods evaluated, the stands examined were sustaining themselves with sufficient recruitment to replace mortality.

Another approach to evaluating whether there are fewer or more oaks today than there were in the past utilizes pollen analysis. Pollen from oak flowers can be identified hundreds or even thousands of years after dispersal. The amount of pollen produced by a given species or genus is thought to correlate positively with the density of those plants present at the time of dispersal. In some lake beds, a pollen record can be determined by examining extracted layers of sediment. Deeper levels of this layer correspond to periods further in the past. By sampling varying depths of these lake beds and analyzing the pollen present, it is possible to estimate the abundance of oaks in different eras. Byrne, Edlund, and Mensing (1991) and Mensing (1998) evaluated sediment cores from lake beds in California and developed pollen diagrams for various species, including oaks. They concluded that, 5,000 to 10,000 years ago, the number of oaks in the Sierra Nevada Mountains increased, most likely as a result of climatic warming. In the last 500 years, however, the density of oaks has been fairly constant, except for the last 120 years. During this recent period, the density of oaks (primarily *Quercus agrifolia* Nee in the Santa Barbara coastal region studied) again increased and the authors of the studies hypothesize that this may have resulted from reduced burning by Native Americans and changes in grazing and woodcutting practices associated with intensified land use during the mid-nineteenth century.

There is obviously some disagreement about the severity of the regeneration problem and whether inventory assessments reflect real changes in population dynamics or merely natural fluctuations in the levels of recruitment that are normal. It also seems that recruitment levels can vary widely among oak species, from location to location within the state, and even over small distances within stands. As will be pointed out below, there appears to be no single cause for poor regeneration at all locations but rather many different factors that can affect recruitment success at different locations.

Oak Species with Poor Regeneration Rates

The three California oak species that are commonly reported to have regeneration problems are blue oak, valley oak, and Engelmann oak (*Quercus engelmannii* Greene) (Muick and Bartolome 1987; Bolsinger 1988), which are all deciduous white oaks. Blue and valley oaks are widely distributed and endemic to the state, while Engelmann oak has a narrower distribution range, growing only in the southern part of California and extending into Baja California, Mexico (Griffin and Critchfield 1972). In addition to these three species, coast live oak may also have insufficient recruitment to maintain existing stand structures in certain areas (Muick and Bartolome 1986; Bolsinger 1988).

It is common in stands of all of these species to find adequate numbers of seedlings and mature trees but a shortage of saplings or intermediate-sized trees. And while there are locations in the ranges of each of these species where regeneration is insufficient to sustain populations, there are also areas where regeneration appears to be adequate (fig. 2). As a result of this wide range in apparent ability to regenerate successfully, there have been efforts to correlate regeneration with both site and climatic factors, as well as with management history, to determine what is causing success and failure (Davis, Brown, and Buyan 1995; Muick and Bartolome 1987; Swiecki, Bernhardt, and Drake 1997a, 1997b; Lang 1988). While no universal reason for poor regeneration has been identified, several possible causes have been proposed.

Causes of Poor Regeneration

Introduction of Mediterranean Annuals

One widespread theory about why oaks are having more trouble regenerating today than 200 to 300 years ago claims that the change in vegetation, from predominantly perennial bunch grasses to introduced Mediterranean annual grasses and taprooted annual forbs, has created environmental conditions that make it much more difficult for oaks to establish successfully (Welker and Menke 1987). Mediterranean annuals, including bromes, ryes, oats, and filaree, are believed to have spread widely in California during the eighteenth and nineteenth centuries with the advent of widespread grazing (Heady 1977). A detailed study of the flora at the University of California Hastings Natural History Reservation in Carmel Valley reports that introduced annual grasses are now the dominant species in grasslands and in the understory of oak foothill woodlands (Knops, Griffin, and Royalty 1995). This spread of Mediterranean annuals seems to coincide roughly with the decline in oak regeneration, suggesting a possible cause and effect relationship.

Figure 2. This hillside has good blue oak regeneration and a wide range of size classes.

Competition for Soil Moisture. The probable reason why rangeland oaks may have more difficulty regenerating in an environment dominated by annuals is that annuals often deplete soil moisture at more rapid rates than perennials, especially in the early spring when acorns are sending down their roots. Danielson and

Halvorson (1991) compared the growth of valley oaks in proximity to either an alien annual grass or a native perennial and found that seedlings near the annuals grew slower. They concluded that "the introduction of alien annual grasses has reduced valley oak seedling growth and survivorship by limiting soil moisture availability." Gordon et al. (1989) also evaluated competition between blue oak seedlings and several introduced annuals and stated that "competition for soil water with introduced annual species contributes to the increased rate of blue oak seedling mortality observed in woodland systems in California." In contrast, a study that evaluated the competition for soil water between blue oak seedlings and a native perennial bunch grass concluded that "densities of *Elymus glaucus* lower than 50 plants per square meter [5/ft^2]could allow survival and successful establishment of blue oak in understories, and are of relevance to patterns of natural regeneration" (Koukoura and Menke 1995). Finally, Welker and Menke (1990) found that the ability of blue oak seedlings to survive was related to the rate at which water stress developed. Rapid soil moisture depletion rates, which would be expected in oak-annual grass communities, were much more damaging than the gradual depletion rates expected for seedlings growing among perennial grasses.

Livestock Grazing

Livestock grazing is also believed to be a cause of poor rangeland oak regeneration. This theory is supported by the rough coincidence of changing patterns of oak regeneration and widespread introduction and spread of livestock into the state during the Mission Period (Pavlik et al. 1991), beginning in the late seventeenth century. The direct evidence that livestock contribute to reduced regeneration is that both cattle and sheep browse oak seedlings, as well as consume acorns. At the University of California Sierra Foothill Research and Extension Center (SFREC), for instance, it is easy to find small oak seedlings that have been heavily browsed or trampled by cattle. A study there found that saplings were much more likely to occur in nongrazed plots than in currently grazed plots (Swiecki, Bernhardt, and Drake 1997a). Heavy grazing, especially over many years, can also indirectly affect oak recruitment because it increases soil compaction and reduces organic matter, both of which can make it more difficult for oak roots to penetrate downward and obtain moisture (Welker and Menke 1987).

There may be other factors inhibiting oak regeneration, as well, so that livestock removal alone may have little impact. In a statewide oak regeneration assessment, Muick and Bartolome (1986) reported that the presence or absence of livestock was not sufficient to explain the pattern of oak regeneration. And Griffin (1973) stated that "experiences in nongrazing areas, such as the Hastings Natural History Reservation, suggest that even without cows, sapling valley oaks may be scarce."

Increased Rodent Populations

A consequence of the change in range vegetation from predominantly perennials to annuals is a change in the number and types of seeds present. It is possible that this change in flora has been accompanied by changes in certain rodent populations that feed primarily on the seeds of the introduced annuals. Since several species of rodents eat acorns and oak roots, higher populations of these animals could cause sufficient damage (see **Animals that Damage Acorns and Seedlings** in chapter 4) to inhibit regeneration in certain locations. Unfortunately, no one was counting gophers, squirrels, or voles two centuries ago, so it is hard to know whether their populations and impacts on oak regeneration have dramatically changed since then.

Changing Fire Frequencies

Another theory for poor regeneration concerns fire. Historical fire frequency rates in foothill woodlands are different today than they were in presettlement times when there was little effort to put out naturally occurring fires (Lewis 1993). In addition, Native Americans regularly burned oak woodlands to keep areas open for hunting, stimulate the sprouting of plants used for various products, facilitate acorn collection, and reduce populations of several insects that damage acorns (McCarthy 1993).

While there was a period of even higher fire frequency around the middle of the nineteenth century (Mensing 1991), and burning by ranchers was relatively common up until the early part of the twentieth century, fire frequencies in the last 60 years have greatly decreased as a result of intensive fire suppression activities (McClaran and Bartolome 1989). This has caused an increase in brush and a buildup of fuels in some understories, especially in the denser woodlands of the Sierra Foothills. Since foothill oaks evolved with, and are adapted to, fire, the change in fire regimes may have adversely affected oak regeneration. Because postfire sprout growth can be rapid, fires in the past may have contributed to oak establishment and continuation (Plumb and McDonald 1981; McClaran and Bartolome

1989). Also, fuel buildup as a result of fire suppression may have created conditions unfavorable for recruitment (Mensing 1992).

There is little evidence to support the theory that changes in fire frequencies have influenced oak regeneration. White (1966) concluded that fire probably played hardly any role in modifying the structure or composition of foothill woodlands in a study area in the Carmel Valley since stands unburned for at least 25 years showed no greater or lesser density of oak seedlings than in recently burned stands. Allen-Diaz and Bartolome (1992) also reported that prescribed burning at the University of California Hopland Field Station in Mendocino County did not affect blue oak seedling recruitment. And Swiecki and Bernhardt (1999), examining the effects of a wildfire on blue and valley oak seedlings, could find no growth or survival advantage associated with burning.

Changing Climate

Global climate change, and specifically a warming trend in California, has also been hypothesized as a factor influencing regeneration success. According to this hypothesis, populations at the edge of some oak species distribution ranges may no longer be able to regenerate and survive because they have not adapted to changed climatic conditions (Bayer, Schrom, and Schwan 1999). Thus, blue oak in the hotter and drier portions of its range may have more difficulty regenerating than in areas where conditions are less harsh. To date, there has been no research to verify this hypothesis.

The Pulse Theory of Regeneration

Finally, it is possible that the apparent shortage of oak saplings may not really signal a regeneration problem but only a lull in natural recruitment levels that happen in spurts or pulses. These pulses may only happen when a rare combination of events, such as low grazing and browsing pressures, good acorn years, and wet winters, occur simultaneously (Griffin 1973). Good regeneration may only take place once or twice a century because the necessary events occur simultaneously so rarely. For very long-lived species, such as oaks, however, these infrequent pulses may be perfectly adequate to sustain populations.

At present, there is not much evidence to support this theory, since studies evaluating the ages of blue oak (Kertis et al. 1993; McClaran 1986; Mensing 1991; White 1966) tend to indicate that seedling recruitment occurs irregularly, but continuously, over long intervals, rather than during short, distinct periods of simultaneous establishment. A significant exception to this pattern, however, is in stands where most of the trees have originated at the same time following fire or cutting (see **Stump Sprouting as a Mechanism of Natural Regeneration**, below).

Is There a Regeneration Problem?

Regardless of the cause of the problem, owners and managers of hardwood rangelands need to evaluate their oak stands to determine if there is adequate recruitment for maintaining stand density or if steps need to be taken to establish new trees. Figure 3 shows a decision key (Lang 1988) to assess oak regeneration. Regeneration is not a problem if there are enough seedlings and saplings present to replace the trees that are expected to die. Neither is there a problem (at least for 20 to 30 years) if the canopy is at the desired level, all overstory trees are healthy, and existing management practices do not adversely affect them. There is a problem, however, if seedlings and saplings are scarce or if a higher stand density is desired.

A Model for Oak Regeneration

Recently, Swiecki and Bernhardt (1998) have argued that blue oak recruitment is often naturally dependent on advanced regeneration and commonly occurs when gaps are created in stands, allowing sufficient light to reach the ground. Advanced regeneration consists of seedlings originating from acorns that are able to survive under the shade of mature trees, but remain small and stunted because of competition and environmental limitations, forming a "seedling bank" for future growth. When a tree falls down, for instance, and suddenly opens up the area in which the seedlings are growing, they receive much more light and have access to greater amounts of moisture and nutrients. They are then able to grow more rapidly and become saplings. However, grazing by livestock or wildlife can reduce the reproductive potential of blue oak by damaging or killing advanced regeneration through repeated browsing that depletes or eliminates the seedling bank over time. Grazing can also suppress the vertical height growth of released seedlings that are shorter than the browse line. Under current grazing management, even when gaps are created, there may simply not be enough seedlings in many locations to respond to new openings.

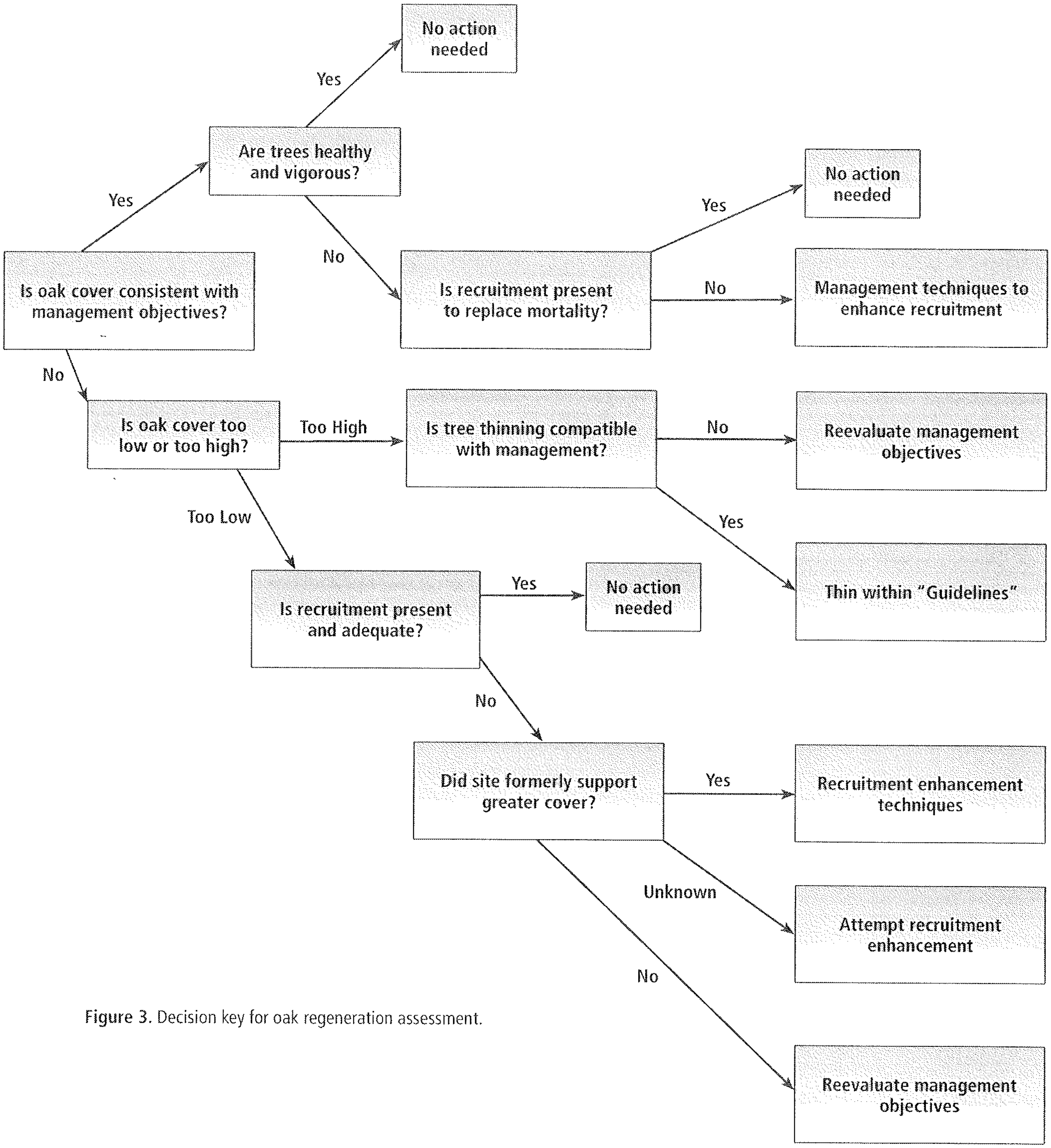

Figure 3. Decision key for oak regeneration assessment.

Stump Sprouting as a Mechanism of Natural Regeneration

There is no doubt that many of the oak trees that are alive today originated from sprouts that grew from a stump after the top was killed by fire or felling. Most stump-origin trees are easily recognized because they have multiple stems. The number of stems tends to decline with age, and older trees often have two or three main trunks. In areas where fire destroyed the stand, or where all of the oaks were cut down at the same time, most of the trees have several stems, and tree-ring studies reveal that many originated simultaneously (McClaran and Bartolome 1989; Mensing 1988).

The ability of oaks to sprout from their base following death of the aboveground portion of the tree varies by species, size of the individual tree, and environmental conditions at the site. Generally, sprouting is greater for evergreen or live oaks than for deciduous oaks; for smaller diameter stumps; and for trees growing in moister environments. While blue oak is commonly thought of as a weak sprouter compared to tan oak and California black oak (McDonald 1990), Standiford et al. (1996) found that 54 percent of blue oaks sampled in a study in the northern Sacramento Valley sprouted, even though many stumps had originally been treated with herbicides to prevent regrowth. In another large blue oak sprouting study at five sites throughout the state, almost two-thirds of the harvested trees sprouted within 2 years of harvest (McCreary et al. 1991). In general, the smaller stumps tended to sprout more, but this study detected no differences in sprouting among the four seasons of harvest, in contrast to Longhurst (1956) who reported higher sprouting for blue oaks harvested in winter.

The 1991 sprouting study also compared stumps that were protected from livestock and deer browsing to unprotected stumps. We recently assessed all trees in this study 10 years after harvest and found that protection had a tremendous effect. While the number of protected stumps that had at least one living sprout was initially higher than it was for unprotected stumps, these differences increased greatly over time. Between 1989 and 1997 the percent of protected stumps with living sprouts went down from 67 to 54 percent. Over the same interval, the percent for unprotected stumps diminished from 59 to 14 percent. Clearly the ability of sprouts to survive over time was greatly influenced by browsing.

It is not clear how many times oak stumps can sprout—several perhaps, but certainly not indefinitely. Therefore, even if sprouting is vigorous and nearly 100 percent, it will eventually be necessary for at least a portion of replacement trees to come from acorns if the stand is to be sustained over the long run.

2

Acorn Collection, Storage, and Planting

Acorns, the fruit of oak trees, contain a single seed. Compared to the seeds of most woody plants, acorns are large and contain a considerable amount of stored food. This helps ensure that they have sufficient energy to grow a large root system before producing shoots, leaves, and the photosynthetic apparatus necessary to manufacture food and become self-sufficient. This can be a great advantage in Mediterranean climates where early root development can be vital since it allows plants to more quickly reach deeper soil horizons where more moisture is available. However, there are also disadvantages of acorns compared to the seeds of some other woody plants. They are recalcitrant and cannot be dried or frozen to prolong storage. This creates problems because it means that acorns deteriorate rapidly and generally cannot be stored for more than one season. Because acorn crops tend to fluctuate from year to year, the inability to store acorns for very long periods means that planting efforts are largely dependent on current crops, which cannot be predicted with accuracy.

The *Quercus* genus can be divided into two main subgenera: the white oaks (section *Quercus*, formerly called *Lepidobalanus*) and the red or black oaks (section *Lobatae*, often known as *Erythrobalanus*) (Sternberg 1996). While there is also an intermediate group in California (section *Protobalanous*), it will not be discussed here. These subgenera have basic differences in wood structure, leaf morphology, and bark characteristics, as well as in acorn physiology. The length of time it takes from pollination and fertilization to acorn maturity is different for white and black oaks. Acorns from white oaks usually require only one year to mature, while those from black oaks (coast live oak is an exception) generally need 2 years.

Flowers on California oaks become visible in the spring, about the time the deciduous oaks are producing a new crop of leaves; both male and female flowers occur on the same tree. The male flowers, or catkins, produce clouds of pollen that are carried by wind to the female flowers, which are small and inconspicuously located in the angle between a new leaf and twig (Keator 1998). The appearance of abundant flowers, however, does not guarantee a large acorn crop (Cecich 1993). For most oak species, acorns mature and fall to the ground in the late summer and early fall. At higher elevations, this can be delayed, and weather conditions can also influence the ripening and falling dates.

Variable Acorn Crops

It has long been known that acorn production varies significantly from year to year (Sudworth 1908; Jepson 1910). In years with good acorn crops, large individual trees can have many thousands of acorns, while, in bad years, it can be difficult to find a single acorn on the same tree, or even on most of the trees in a stand or in a region. Masting cycles have been reported to vary greatly among the California oaks species examined, with good mast years occurring every 2 to 6 years.

There have been several inventories of acorn production on native California oaks. In 1977, the California Department of Fish and Game began assessing annual acorn production from 360 blue oak trees at the Dye Creek Ranch in Tehama County (McKibben and Graves 1987). They found that, in addition to highly variable annual acorn production patterns, there were certain trees in stands that were consistently better or worse producers than others. Even in heavy acorn years, about a quarter of the sampled trees had few or no acorns.

Weather As a Factor

For nearly two decades, Walt Koenig and others at the University of California Hastings Natural History Reservation in Carmel Valley have also evaluated the acorn production of several species of native California oaks, including blue and valley oak (Koenig et al. 1991; Koenig et al. 1996; Koenig et al. 1999; Koenig and Knops 1995; Koenig and Knops 1997). They have been particularly interested in finding trends in production patterns in California that are related to environmental variables that may explain why acorn crops are much larger in some years. The closest correlation they have found is related to weather at the time of flowering. When conditions are dry and warm at flowering, crop sizes for blue and valley oak tend to be larger compared to years when it is cold and wet during the same period (Koenig et al. 1996). Since acorns are wind pollinated, dry and warm conditions seem to favor pollination and subsequent acorn production. Interestingly, because some oak species, such as California black oak (*Quercus kelloggii* Newb.) and interior live oak (*Quercus wislizeni* A. DC.), require 2 years from flowering to acorn production and others, such as blue oak and valley oak, require only 1 year, it follows that production patterns between 1- and 2-year species could be very different, while trends within these groups should be similar. To date, these studies have found high synchrony throughout California within the 1-year species, but less for those requiring 2 years (Koenig et al. 1999).

Geographic Synchrony

This research has also evaluated whether or not there is geographic synchrony within individual species, that is, when acorn crops are good for blue oaks in the northern Sacramento Valley, are they also likely to be good along the central California coast or even farther south? Preliminary evidence suggests that there is widespread geographic synchrony, possibly on a statewide scale, among some of the 1-year species (especially blue oak), but much less synchrony among the 2-year species (Koenig et al. 1999).

Collecting Acorns

Timing

Acorns should be collected shortly after they are physiologically mature. While there are various indicators, such as moisture content, levels of carbohydrate, and acorn color, that have been used to predict ripeness for oak species in other parts of the country (Bonner and Vozzo 1987), the easiest and best characteristic we have found for blue and valley species is the ease with which acorns can be dislodged from the acorn cupule or cap. When acorns are ripe, they can be easily removed from the cap by gentle twisting. If they are not ripe, the caps are difficult to remove and some of the fleshy meat may be torn off the acorn and stay attached to the cap when separated. Because immature acorns cannot be ripened artificially after picking (Bonner 1979), acorns should not be collected until they are ripe. For blue oak, McCreary and Koukoura (1990) found that viable acorns could be collected over a fairly wide interval, extending from late August until mid October. Generally, acorns should be collected a few weeks after the first ones begin to drop. The early fallers often contain a large percent that are diseased or damaged by insects (Swiecki, Bernhardt, and Arnold 1991) and should be avoided.

Sensitivity to Drying

After collection, acorns are especially sensitive to drying, and their ability to germinate can decrease rapidly with even small losses in moisture content. McCreary and Koukoura (1990) found that even a 10 percent reduction in fresh weight of mature acorns resulted in nearly a 50 percent decrease in germination, and all acorns that lost 25 percent or more of their moisture

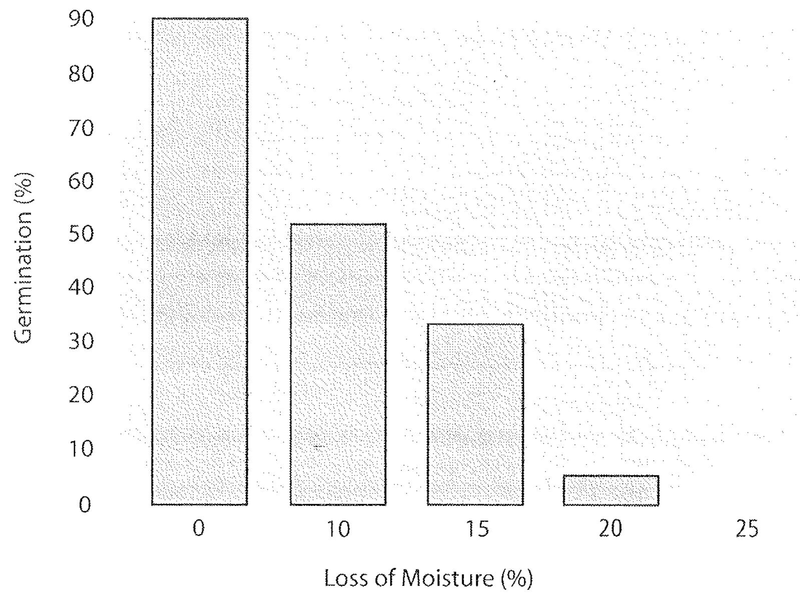

Figure 4. Acorn germination decreases with moisture loss.

failed to germinate (fig. 4). Because acorns can dry rapidly in the late summer and early fall when they drop to the ground, it is better to collect them directly from tree branches. Other researchers have reported that tree-collected acorns (fig. 5) have better germination than those collected from the ground (Teclaw and Isebrands 1986) and that damage ratings for ground-collected acorns are higher (Swiecki, Bernhardt, and Arnold 1991). On the ground, acorns can be rapidly consumed by animals. Sometimes, however, it can be impossible to collect directly from branches that are too high to reach. In these instances it is best to come back to collect acorns from the ground several times so that none remains exposed for long periods. If acorns have partially dried out, it may be possible to improve their quality by rehydrating them. Gosling (1989) found that the germination capacity of English oak (*Quercus robur* L.) acorns that had lost moisture could be improved by resoaking them for 48 hours prior to storage. However, it is best not to allow acorns to dry out in the first place.

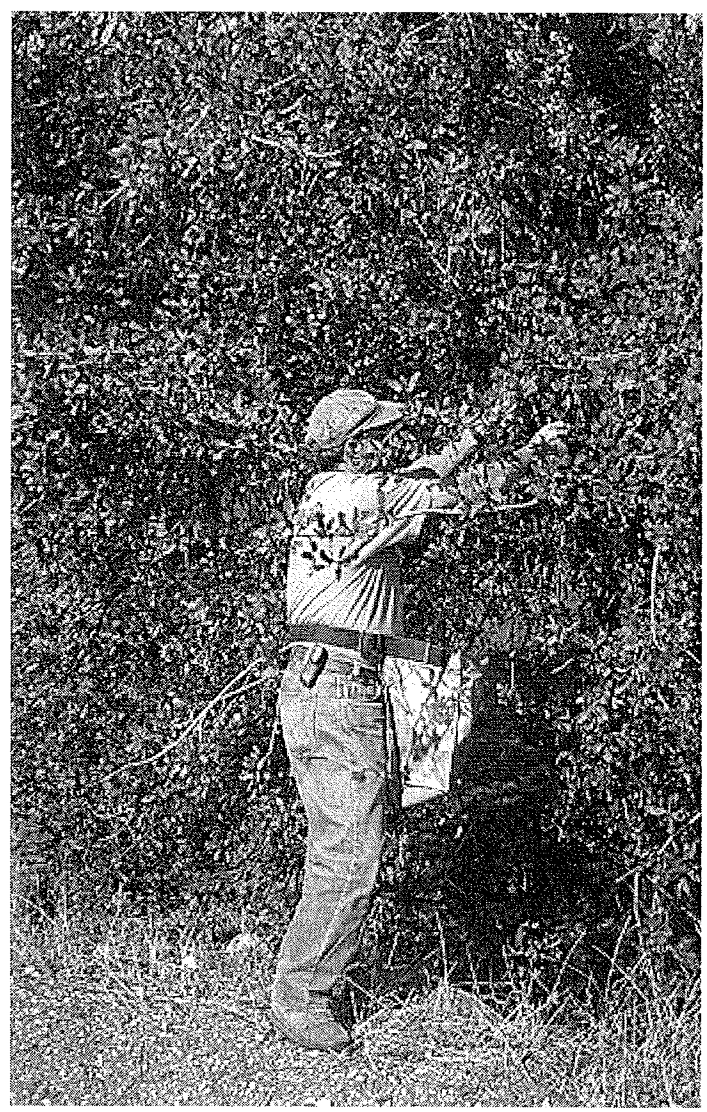

Figure 5. Using a waist bag frees both hands to collect acorns from branches.

Acorns can also be knocked to the ground from tree branches using long plastic or bamboo poles. However, it is essential to do this when the acorns are ripe. If done too early, acorns do not dislodge from the caps and remain on the tree. If too late, acorns have already fallen and may have deteriorated or been lost to animals. We have gathered acorns this way for blue oaks using tarps placed under the limbs to collect acorns as they fall (fig. 6). But many acorns knocked from the tree this way still have their caps, which must be removed prior to storage. Care should be taken not to beat the branches too forcefully so that tender new growth and even older shoots do not fall.

Sorting Acorns

Any collection of acorns contains individuals of varying quality and potential to germinate. If acorns are collected directly from the tree branches and obviously hollow or damaged acorns are discarded as they are picked, the percentage of viable acorns collected is very high, and it is generally not necessary to sort them further. But acorns collected from the ground usually have a much higher incidence of damage, and the quality of the seed lot can be improved considerably by sorting. The easiest, least expensive, and fastest sorting method is the float test. Acorns are dumped into a sufficiently large container filled with water. They are then stirred and left for several hours to either settle to the bottom, or float to the top. "Floaters" are discarded, and "sinkers" are retained. Studies have evaluated the float test for various collections of northern red oak (*Quercus rubra* L.) and found that it works reasonably well for culling damaged or insect-infested acorns (Gribko and Jones 1997; Teclaw and Isebrands 1986). The float test identifies those acorns that are hollow or damaged inside. For example, if an acorn has been infested by weevils, and a large part of the cotyledons (the white, fleshy material that provides energy and nutrition for early seedling growth) has been consumed, it will likely float.

Similarly, if acorns have been exposed on the ground for some time before collection and have desiccated and shrunk, there might be an internal air pocket that causes them to float. Finally, some acorns drop from the tree before becoming fully developed. These will also float. While the float test is inexpensive and easy, it is not 100 percent foolproof. In large seed lots, there are always some floaters that will germinate, and some sinkers that do not. Gribko and Jones (1997) reported that the float method was much better at identifying damaged, rather than sound, northern red oak acorns. That is, most of the damaged acorns floated, but many sound acorns failed to sink. However, in heavy production years, acorns are plentiful and discarding some sound acorns is probably not important. But when acorns are very scarce, it is important to retain each acorn that might germinate, so the float test may not be helpful.

Another method of sorting acorns is to select them according to size. This is fairly easy to do, and there have been reports for some oak species that larger acorns perform better (Korstian 1927) or produce larger seedlings (Matsuda and McBride 1986). A trial to evaluate the effect of acorn size on blue oak seedling performance was conducted at the Sierra Foothill Research and Extension

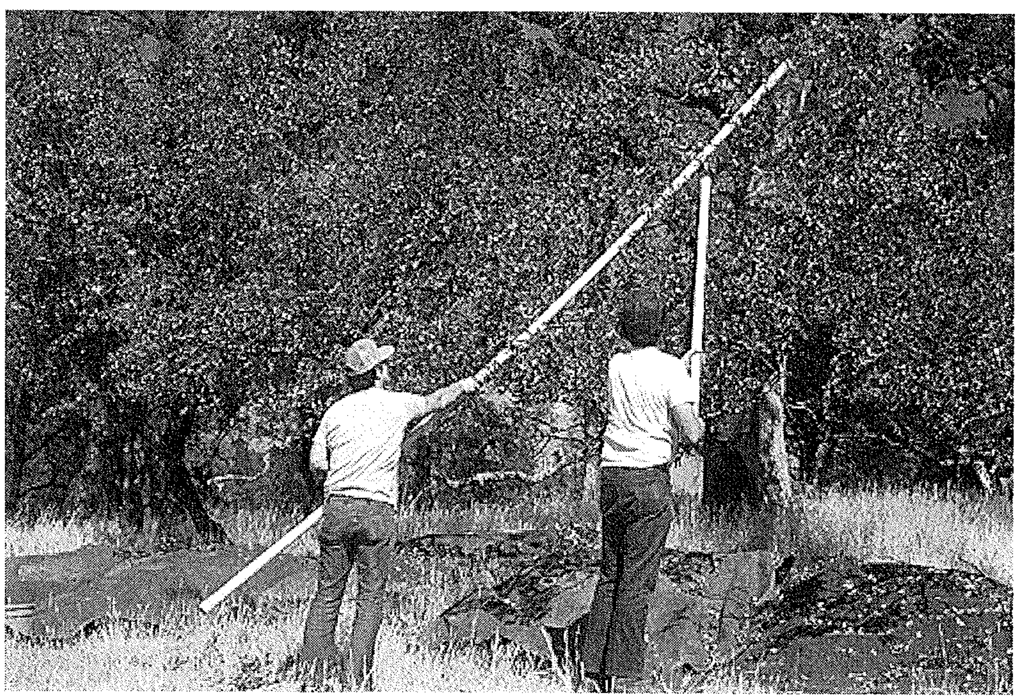

Figure 6. Long poles can be used to knock ripe acorns onto tarps.

Center between 1987 and 1989 (Tecklin and McCreary 1991). Results indicated that larger acorns did, in fact, produce larger seedlings, including both larger roots and larger shoots. However, after 2 years there were no significant differences in field survival between seedlings grown from acorns of different sizes.

Stratification

Dormancy in seeds can be defined as a state that prevents germination under environmental conditions that would otherwise be favorable for growth (Olson 1974). To overcome or break dormancy and stimulate subsequent germination, some seeds need a period of cold, wet conditions. Plants have evolved this delaying tactic to ensure that they do not germinate before seasonal changes make survival of the plant likely. Thus, even though there may be a week of spring-like weather in late January, these seeds will not germinate because they have not yet been naturally exposed to the necessary period of winter-like conditions. Over the long run, this is advantageous in environments where frosts following unseasonable warm spells are likely because early germination could prove lethal to the new shoot.

White Oaks

As noted previously, the *Quercus* genus can be divided into two main subgenera: white and black oaks. White oaks in California have little or no embryo dormancy. This means that they do not have to be exposed to any special environmental conditions and are ready to germinate soon after they have been gathered. Anyone who has collected valley or blue oak acorns and stored them in the refrigerator for any length of time can testify to the fact that these acorns begin germinating within a few weeks or months, even in such a cold environment. If left long enough, the acorns can form a tangled mass of elongated radicles. It can be difficult to plant (and sometimes even to separate) such acorns, but research in the southern United States suggests that it is not essential to keep the radicles intact. Bonner (1982) found that breaking radicles prior to sowing in a nursery did not adversely affect seedling production for any of the three oak species he tested. At the University of California Sierra Foothill Research and Extension Center (SFREC), we also found that when long radicles of blue oak were cut back to a .4-inch (1-cm) length, they grew as well as acorns with intact radicles (McCreary 1996). However, when the radicles were cut all the way back to the acorn, the acorns failed to produce shoots.

Black Oaks

Acorns from this group generally have embryo dormancy although it is variable, and there can be differences in dormancy even within species (Bonner and Vozzo 1987). After collection, black oak acorns need stratification, a period of artificial, winter-like conditions that helps break dormancy and allows the acorns to germinate. According to Olson (1974), stratification for oaks "should be in moist, well-drained sand, sand and peat, or similar material for 30 to 90 days at a temperature of 32° to 41°F [0° to 5°C]." We have found that it is also possible to provide stratification for black oak acorns in California by soaking the acorns for 24 hours and then putting them in a refrigerator (but not a freezer) for 30 to 90 days, though precautions must be taken to ensure that acorns do not dry out.

Our experience with black oaks in California has been limited to California black oak (*Quercus kelloggii* Newb.), interior live oak (*Quercus wislizeni* A. DC.), and coast live oak. All of these species have germinated in storage without stratification, indicating that they do not have particularly strong dormancy or stratification requirements. Matsuda and McBride (1989b) evaluated germination of seven California oak species and found that there were fast and slow germinators, with white oaks generally in the former, and black oaks in the latter group. Longer stratification periods increased the rapidity of germination after sowing for all of these species. However, even some black oak acorns not receiving stratification eventually germinated. For tree seeds in general, stratification tends to make germination more even, reducing the interval between early and late germinators. It also widens the range of conditions over which seeds can subsequently germinate. Both of these effects can be helpful when sowing acorns in a greenhouse or nursery where it is desirable to produce seedlings of uniform size.

Storing Acorns

After collection, acorns should be stored in a refrigerator or cooler preferably at a temperature just above freezing (between 33.8° and 37.4°F [1° and 3°C]). They should be placed in plastic bags that act as moisture barriers but allow some gaseous exchange. Prior to storage, the acorn caps should be removed. Because acorns continue to respire during storage, some gas exchange with the atmosphere is necessary and airtight storage containers should be avoided. It is therefore recommended that plastic bags be kept partially open at the top so that the moisture that tends to condense on the insides of the bags can evaporate and does not accumulate. Nevertheless, it is important to regularly check acorns to make sure they are not drying out.

Keeping acorns cool during storage serves several functions. First, it tends to slow respiration, which utilizes energy and can deplete carbohydrate reserves. Second, it slows the tendency for sprouting which is especially common for white oaks. And third, refrigeration tends to reduce the incidence of harmful microorganisms that can damage or kill acorns. To further retard molds, some restorationists suggest treating acorns before storage or placing fungicides inside storage bags. Bush and Thompson (1990) recommend rinsing acorns in a solution of ½ cup (118 mL) household bleach per 1 gallon (3.8 L) of cool water to kill harmful fungi. To prevent disease problems, Adams et al. (1991) dusted acorns with the fungicide Captan prior to storage. We have generally found that treating acorns prior to storage is not necessary as long as acorns are stored at the temperatures and conditions described above, and as long as they are not stored for extended periods of time. However, if molds on acorns during storage become so extensive that the radicles become discolored and slimy, it is best to discard them.

There are also several insects that can damage acorns (see **Animals that Damage Acorns and Seedlings** in chapter 4), but most damage occurs before collection. Moreover, it is difficult to kill these insects once they are inside the acorns without damaging the acorns themselves.

White oaks cannot generally be stored for more than a single season, but some researchers have reported that acorns from certain black oak species can be stored for at least 3 years (Bonner 1973). However, little research on prolonged storage has been conducted for California species. We have kept both California black oak and interior live oak acorns in a refrigerator for more than a single season but have observed that the number that subsequently germinate drops dramatically, such that only a few acorns remained viable into the second year.

Testing Acorn Quality

There may be instances when it is important to accurately determine acorn quality. Such information may be valuable before proceeding with a large-scale collection, or to assess whether temporary storage or handling procedures have been detrimental. Seed tests are also important for nurseries that need to calculate sowing densities. The most accurate measure of potential acorn performance is to incubate a representative sample of intact acorns under environmental conditions that bring about germination. Standard conditions recommended by the Association of Official Seed Analysts (AOSA 1993) for conducting germination tests on acorns are a day temperature of 86°F (30°C) and a night temperature of 68°F (20°C), with an 8-hour photoperiod (length of daily light interval). It is also critical that the acorns be placed on a moist medium, such as sand, sand and peat, or vermiculite, and not be allowed to dry during the test. These tests provide an estimate of germination percentage. Unfortunately, germination tests on the intact acorns of many oak species can take 2 months or more to complete, and this is often too long to wait. One way to speed tests is to partially dissect the acorns before sowing them. Cutting acorns in half (discarding the cap end) and peeling away the pericarp (acorn skin) can reduce the germination time to about 3 to 4 weeks. However, even this is frequently too long. Consequently, a number of more rapid viability tests have been developed and may be of use in special situations.

Recommended Acorn Collection and Storage Procedures

- Collect acorns in the fall, several weeks after the first ones have started to drop and when those remaining on the tree can be easily dislodged from the acorn cap by gentle twisting.
- If possible, collect acorns directly from the branches of trees, rather than from the ground.
- If acorns are collected from the ground, place them in a bucket of water for several hours, and discard floaters.
- Stratify acorns from the black oak group by soaking them in water for 24 hours and then storing them in a cooler or refrigerator (33.8° to 37.4°F [1° to 3°C]) for 30 to 90 days before sowing.
- Store acorns in a cooler or refrigerator in loosely sealed plastic bags, but do not store acorns from the white oak group for more than 1 or 2 months before planting to ensure greatest viability.
- If acorns start to germinate during storage, remove and plant them as soon as possible.
- If mold develops during storage, and acorns and radicles are discolored and slimy, discard acorns.

A viability test identifies those seeds that are alive, but that does not necessarily mean that they are capable of germinating. Bonner and Vozzo (1987) describe three options for quick viability tests. The first, simplest, oldest, crudest, and probably best technique is a cutting test. In this test, a sample of acorns are cut in half and those with clean, firm, and healthy-looking cotyledons are considered viable. Those that are entirely empty or in which the embryo appears undeveloped, shriveled, moldy, or insect-damaged are not viable.

Another method of testing is X-radiography. This is a quick and nondestructive technique for identifying empty and damaged fruits and seeds of most species. Unfortunately, for acorns it can be difficult to interpret because the high moisture content of live acorns renders the X-ray images opaque.

Finally, there is the tetrazolium test. This relies on the premise that only living cells have the enzymes capable of converting a colorless solution of tetrazolium salt into a colored precipitate. Although this test has been widely applied to the seeds of a large number of species, it is only moderately successful for acorns (Bonner 1984). This is probably because acorns contain secondary compounds that interfere with the staining reaction.

Genetic Considerations

Genetic Differences within Oak Species

Restoration is defined as bringing something back to a former or normal condition. For restoration, therefore, only a given species of oak should be planted in areas where it naturally grows or grew in the past. But even within an oak species, the source of the acorns must be considered. Both blue oak and valley oak are widely distributed species in California, ranging in latitude over much of the length of the state and in elevation from near sea level to 5,600 feet (1,700 m) for valley oak (Griffin and Critchfield 1972), and to over 4,500 feet (1,400 m) for blue oak (McDonald 1990). Clearly, there is a very wide range of environments in which different populations within these species grow. For instance, blue oak grows on Santa Cruz and Santa Catalina Islands, as well as at lower to middle elevations in the northern Sierra Nevada. While the coastal environment is generally temperate and mild, growing seasons in Northern California are shorter, and frosts commonly occur in late spring. If acorns collected from coastal trees were planted in the north, they may grow quite well for a number of years. But in the life span of an oak tree (which can be 200 to 300 years), it is likely there will be an environmental extreme that they are not genetically adapted to. A serious freeze in late spring, for instance, could seriously damage or kill a tree from a coastal source, while local trees may suffer few negative effects.

Although there has not been a lot of research on the genetics of native California oaks, Rice, Richards, and Matzner (1997) found evidence for local adaptation of blue oak populations collected at the University of California Sierra Foothill Research and Extension Center and at the University of California Hopland Research and Extension Center. However, Riggs, Millar, and Delany (1991) found only relatively small genetic differences within valley and blue oak populations using biochemical assay techniques and could detect no geographic pattern in variation in these biochemical markers.

Genetic Contamination

Another potential problem of moving oaks from one locale to another is genetic contamination. Oaks are wind pollinated and require pollen from male flowers to pollinate and fertilize female flowers. If pollen-producing trees are from off-site locations and contain genetic traits poorly adapted to the area where they are growing, there is a risk that they could introduce these ill-adapted traits into the population via newly produced acorns. While there certainly is debate over how serious a threat this is for oaks as well as for other species, it makes sense to avoid this potential danger when possible. It is, therefore, recommended that acorns be collected as near to the planting site as possible. Furthermore, to ensure adequate genetic variability within the local population, Lippitt (1992) recommends collecting acorns from at least 15 trees at any given site.

Timing of Acorn Planting

As mentioned above, blue and valley oak acorns generally ripen in late summer to mid fall. However, at this time soils can still be extremely dry because the first heavy, fall rains may not have occurred. While even fairly dry soils can have relatively high humidities under the surface, these soils can also be extremely hard, and, even if acorns do germinate, root penetration is likely difficult. We, therefore, recommend that acorns are only directly planted in the field after there has been sufficient rainfall to soak the soil at least several inches down. But how soon after these rains should acorns be planted? In a trial at the University of California Sierra Foothill Research and Extension Center with blue and valley oaks, we compared field performances of acorns sown at monthly intervals for 5 months starting in early November

(McCreary 1990a). Acorns for each species were collected from single trees in early October and were stored in the refrigerator for intervals ranging from 1 to 5 months before planting. We then recorded emergence date, total emergence, first- and second-year heights and diameters, and survival of seedlings in the field. There were profound and consistent effects of acorn planting date, with better performance for those that were sown earlier. They tended to emerge earlier, have higher survival, and grow more. While early emergence might increase the risk of frost damage, we have never observed such damage at SFREC. Sowing acorns on the last date in early March was particularly harmful since the seedlings seemed to get such a late start that they apparently were not able to grow a very large root system before the summer dry period. Based on these results, we recommend that blue and valley oak acorns be planted early in the season, as soon as possible after the soil is sufficiently wet. As a rule of thumb, planting should take place no later than the end of January, and even this may be too late in areas with less rainfall and shorter winters.

How to Sow Acorns

Planting Depth

When directly sowing acorns in the field, it is important to bury them since the likelihood of depredation, as well as desiccation damage, is much greater for exposed rather than buried acorns. In a study with blue, valley, and coast live oaks, Griffin (1971) found that burying acorns did not eliminate rodent damage but did reduce losses. And Borchert et al. (1989) reported that recruitment of buried blue oak acorns was twice that of surface-sown ones. We generally sow acorns ½ to 1 inch (1.0 to 2.5 cm) deep, but in some situations it may be better to plant them deeper. In an area where rodents were a threat, Tietje et al. (1991) found that, in general, emergence was better for blue oak and valley oak acorns planted 2 inches (5 cm) in the ground because shallower plantings (½ in [1 cm]) had much higher depredation, while deeper plantings (4 in [10 cm]) made it too difficult for shoots to grow up through to the soil surface. However, if acorn depredation is not a serious concern, shallower plantings are generally preferred.

Recommended Methods for Sowing Acorns of Rangeland Oaks in the Field

- Sow acorns in the fall and early winter, as soon as soil has been moistened several inches down.
- If possible, pregerminate acorns before planting and outplant when radicles are ¼ inch to ½ inch (½ to 1 cm) long.
- Cover acorns with ½ to 1 inch (1 to 2 ½ cm) of soil.
- If acorn depredation is suspected as a serious problem (high populations of rodents are present), plant deeper, up to 2 inches (5 cm).
- If acorns begin to germinate during storage, outplant as soon as possible with the radicle pointing down. Use a screwdriver or pencil to make a hole in the soil for the radicle.
- If radicles become too long, tangled, and unwieldy to permit planting, clip them back to ½ inch (1 cm) and outplant.
- If acorn planting spots have aboveground protection (treeshelters), and acorns have not been pregerminated, plant two or three acorns per planting spot and thin to the best seedling after 1 year. (See chapter 4.)
- Keep planting spots free of weeds for at least 3 years after planting. (See chapter 4.)

Pregermination

We have found that by pregerminating acorns before field planting, more than 90 percent will initially grow. Pregerminating acorns is easily done by filling pie pans or other shallow dishes with moist vermiculite, sand, or peat. Acorns are then placed on their sides and gently pressed into the medium (fig. 7). It is important that the material stay moist, but not overly saturated, while the acorns are germinating. The trays can be placed at room temperature on a table, windowsill, or bench for observation. Blue oaks generally begin germinating in 1 to 2 weeks, as evidenced by a white tip, or radicle, protruding from the pointed end of the acorn. They are then ready to outplant. When planting pregerminated acorns with developed radicles, use a pencil, screwdriver, or other pointed object to make a hole in the soil and carefully position the acorn in the hole with the radicle pointing downward. Acorns can then be covered as described above.

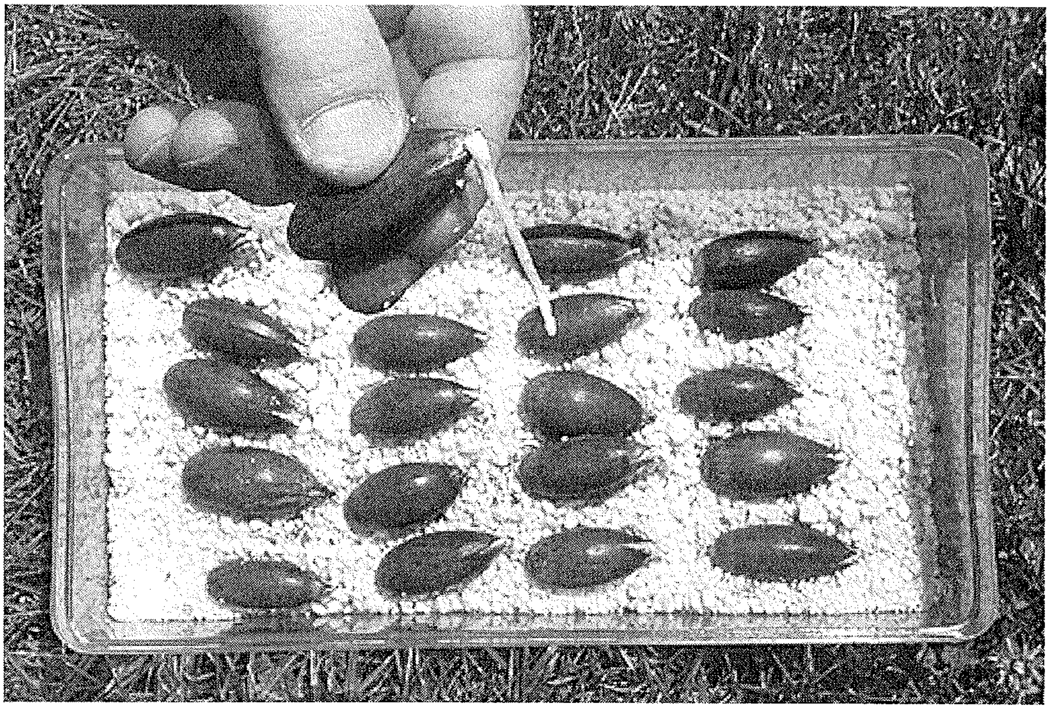

Figure 7. Place acorns in trays of moist vermiculite for easy pregermination.

Multiple Seeding

When directly planting acorns, it is a good idea either to sow those that you are sure will germinate or several at each planting spot to ensure germination of at least one individual. Some restorationists feel it is important to plant two or three acorns per planting spot (Bush and Thompson 1989). This is particularly important if planting spots are protected with cages or tubes because such planting requires considerable expense and effort. Since acorns are generally easy to obtain, multiple seeding is far less expensive than replanting. However, multiple seedlings should eventually be thinned to the single best plant, which is not always easy to do inside of tubes. This can be time consuming and expensive, and, if acorn quality is extremely good and expected germination rates are above 90 percent, it is probably not necessary to sow more than one acorn per spot.

Acorn Orientation

Some researchers have questioned how acorns should be oriented when planted. Both the shoot and the root emerge from the pointed end of the acorn, so whether they are planted point up or point down may subsequently affect how seedlings grow. McDonald (1978) reported the results of a field test that compared point up vs. point down plantings of tanoak acorns (*Lithocarpus densiflorus*), a species closely related to *Quercus*. He found that planting point up resulted in earlier and more complete emergence. A study with northern red oak, however, found that, while planting position (point up, point down, or sideways) had no statistically significant effect on seedling survival and growth, acorns lying sideways had the highest average survival (Trencia 1996). In our research trials at SFREC, we have opted to plant acorns horizontally, and this has proven quite effective.

Acorns or Seedlings?

The choice of whether to plant acorns or seedlings depends on a host of factors including availability of suitable planting material and conditions at the planting site. Sometimes it is difficult to obtain seedlings from local sources. Only by collecting acorns yourself can you be sure that your planting will be adapted to local conditions. However, if large numbers of acorn-eating rodents, such as mice or ground squirrels (*Spermophilus beecheyi*), are present, it can be difficult and costly to successfully establish oaks by direct seeding. In these situations, the best solution may be to plant seedlings.

We have conducted several trials to compare the field performance of acorns and seedlings from the same seed source. In one study, we detected very little difference between blue oak seedlings that originated as directly sown acorns and those that were grown for 4 months in containers and then transplanted. Both had over 90 percent survival, and, after 5 years, there were no significant differences in height (McCreary and Tecklin 2001). This is consistent with a previous blue oak trial at the SFREC (McCreary 1996) in which these two stock types were also compared. In the 1996 trial, however, acorns had far greater growth than 1-year-old seedlings planted at the same time. It is important to note that both of these trials were conducted in highly controlled environments, and in less intensively managed wildland settings, transplants might perform better.

Because it is easier and less expensive to directly plant acorns, this method may be preferable in many situations. However, if direct sowing is used, it is important that steps be taken to ensure that acorn depredation will not be a problem since this can negate any benefits that might otherwise be realized. Our plots were kept fairly weed free, and, therefore, there were not many rodents, which are attracted to locations where weed cover is dense (see **Animals that Damage Acorns and Seedlings** in chapter 4).

3

Propagating Rangeland Oak Seedlings

Until a decade ago, there were relatively few native oaks produced for artificial regeneration in California, mainly because there was little demand. Historically, most California oak species have not been considered desirable landscape plants, partly because they had a reputation for growing slowly. Also, few seedlings were commercially grown because oaks in California have never been considered important timber trees. The lack of commercial importance also meant that there was almost no research carried out on how to grow oaks, either in containers or in bareroot nurseries. While such research has been extensive for commercially important eastern oak species, such as northern red oak (Johnson 1988; Ruehle and Kormanik 1986; Thompson and Schultz 1995), in California the propagation methods used have evolved from the growers' experiences and have been based largely on trial and error.

The last decade has seen a significant increase in demand for, and production of, oak seedlings. Oak seedling quality has also improved over the same period, reflecting improvements in nursery husbandry. Nurseries, such as Tree of Life in San Juan Capistrano, Circuit Rider in Windsor, and the California Department of Forestry and Fire Protection L. A. Moran Reforestation Center in Davis, have now been growing oaks for many years. Below are some general comments about propagation methods for container-grown oak seedlings, followed by case histories summarizing production methods used by these three nurseries. For further information about container production practices, consult one of the nurseries listed in appendix A.

Seedling Production in Containers

The vast majority of native oaks produced in California are grown in containers, which range in size from a few cubic inches to large boxes of many cubic feet. In general, oak seedlings tend to put a large amount of energy into producing a taproot with a carrot-like configuration. Seedlings can, therefore, quickly become pot-bound in small containers, meaning the volume of seedling roots produced can exceed the growing space in the container. Planting such stock can result in poor subsequent field performance or even death. It is, therefore, important not to grow seedlings in containers that are too small. Some nurseries start oaks in small sleeves called "liners"

Preparing Potting Mix

Combine the following:

5 ft^3 course peat moss

5 ft^3 course vermiculite

4 ft^3 fir bark (1/8- to 1/4-inch size)

1 lb lime

2 lb slow-release fertilizer granules

or in flats, and then transplant the seedlings to larger containers as they become bigger. In general, better quality oak seedlings are produced in narrower, deeper containers, rather than in wide, shallow containers. For this reason, a common container for raising oaks is a "treepot," with dimensions of approximately 4 by 4 by 14 inches (10 by 10 by 36 cm) although large-scale production is often started and completed in liners or small containers called "plant bands."

Preventing the Formation of Deformed Roots

Oak taproots generally reach the bottom of a container before the shoots emerge from the soil surface. Once at the bottom, these roots tend to circle around unless they are checked or prevented from growing. Such root circling creates a plant that is poorly adapted to growing in the field. Deformed roots can persist for years and even decades after field planting and can cause poor tree growth and lack of stability.

Air Pruning. Many container production systems employ air pruning to thwart root circling. As the seedling roots grow to the bottom of the container, they are exposed to air. This is accomplished by using open-ended containers that are placed on screens or mesh to prevent the soil from falling out while still exposing roots that reach the bottom. Since the air is dry, and roots need moisture, the root tips stop growing. This, in turn, causes the production of lateral branch roots farther up the main root, creating a much more fibrous root system. This type of air pruning is used at the California Department of Forestry L. A. Moran Reforestation Center with excellent results (Lippitt 1992).

Chemical Pruning. There are also commercially available copper compounds that can be painted on the interior of containers. These compounds arrest the growth of root tips (Regan, Landis, and Green 1993). When roots come in contact with these chemicals, they are pruned, causing further root branching and development of a more fibrous root system.

Planting Medium

Oak seedlings grow well in a variety of potting mixes. According to Schettler and Smith (1980), "nearly any reasonable planting medium can be used with good results-as long as it is well-drained."

Fertilizing

Container seedlings generally need to be fertilized within a few weeks after sowing. Fertilizer can be provided in irrigation water or in slow-release fertilizers incorporated into the soil mix. A fertilization regime that has been used successfully is adding 20-20-20 at 100 parts per million of nitrogen in irrigation water, plus micronutrients.

When to Transplant

Most container seedlings are grown for a year or two before transplanting to the field. In some cases, however, the time in the container can be considerably longer as plants are repeatedly transplanted to increasingly larger containers in order to produce large-sized (and very expensive) landscape plants. At SFREC, we have experimented with a shorter production schedule. We collected acorns in October, sowed them in outdoor shadehouses at the California Department of Forestry Nursery in Davis in December, and then planted the young seedlings back at the University of California Sierra Foothill Research and Extension Center in late March. While these seedlings appeared quite fleshy and tender at the time of outplanting, they performed well in the field (McCreary 1996). In fact, in this trial they were superior to 1-year-old container stock in terms of survival and growth. Obviously, it is far less expensive to produce a 4-month-old seedling than one grown for a full year, so this stock type may be suitable in some situations.

Growing Your Own Seedlings

Germination

It is possible to grow your own oak seedlings without sophisticated greenhouses or other equipment. Acorns are easy to collect and germinate, and the requirements for small seedlings are relatively modest. Pregerminate acorns in shallow trays to make sure that all of the acorns that are planted are viable and ready to grow.

Recommended Procedures for Growing Oak Seedlings in Containers

- Grow oak seedlings in tall and narrow, rather than short and wide, containers.
- Select appropriate container sizes and transplant seedlings to larger-sized containers before seedlings become "pot-bound."
- Use containers that promote the pruning of root tips at the bottom.
- Use a coarse, well-drained, potting mix; keep it moist, but not saturated, and make sure it does not dry out during warm weather.
- Ensure seedlings have adequate nutrition by incorporating a slow-release fertilizer into the potting mix or using a balanced, liquid fertilizer in irrigation water.

Containers and Potting Mix

As previously discussed, tall, narrow containers are preferable to short, wide ones. We have had good success with small milk-carton-like boxes that are open at both ends. These are available in a variety of sizes (see appendix A), and a size of 2 by 2 by 10 inches (5 by 5 by 26 cm) seems particularly well suited to growing oak seedlings. These containers are wide enough to lay acorns flat for planting, and tall enough to allow good root development. For growing large numbers of seedlings, the potting mix described in the box on page 20 has worked well. But for growing fewer than two hundred seedlings, it is probably easiest to buy commercially available potting mixes in ¾-cubic-foot bags. Course mixes that have better drainage are preferable to finely textured ones.

To prevent the potting mix from falling out of the open-ended containers, we place a single sheet of newspaper in the bottom of the rack. These decompose about the time the roots reach the base of the containers, but by that time, there is little risk of the soil falling away. Racks should not be placed on a solid surface, but should be elevated slightly or placed on screen, narrow strips of wood, or mesh.

Containers can be kept indoors or outdoors; but if outdoors, the seedlings must be protected from severe freezes. It may also be necessary to make sure that birds or rodents do not remove acorns. While the roots start to grow right away, it may take several months for the shoots to emerge. As noted above, we have found that 4-month-old blue oak seedlings grown this way (sown in containers in December and field planted in March) have performed well in the field, as long as they are irrigated at the time of planting. But since the seedlings are fairly tender and fleshy, they need to be handled and planted carefully.

Other Ways to Grow Oak Seedlings

There are also other ways to grow oak seedlings. A video and manual produced by the University of California Cooperative Extension in Calaveras County, *Oak Tree Project,* (Churches and Mitchell 1990) describes a program to collect acorns and grow seedlings, targeting school and community groups.

Nursery Case Histories Involving Container-Grown Seedlings

Circuit Rider Productions

Circuit Rider Productions is a nonprofit service corporation dedicated to the enhancement of environmental and human resources. Since 1978 they have operated a native plant nursery where they produce plants for restoration and revegetation projects, specializing in site-specific liner stock. From the beginning, they have grown a number of California oak species, including valley, blue, California black, coast live, canyon live (*Quercus chrysolepis* Liebm.), interior live, and Oregon white oaks (*Quercus garryana* Douglas ex Hook.).

Container Types. Many are grown in tapered plastic tubes called "super cells" (1½ inches [4 cm]in diameter and approximately 10 inches [26 cm] deep). These tubes have ribs on the internal walls that help direct roots downward, resulting in air pruning and preventing root circling. Other containers that are used at

Circuit Rider Productions include deepots (2 in [5 cm] in diameter and 10 in [26 cm] deep) and treepots (4 by 4 by 14 in [10 by 10 by 36 cm]). The containers are filled with a well-drained growing medium and are regularly irrigated during the dry season to ensure that the growing medium stays moist, but not saturated. A slow-release fertilizer is incorporated into the potting mix prior to sowing, and liquid fertilizer is added during the growing season. Oaks grown in super cells develop an 8-inch (21-cm) root and a shoot that is about 4 to 8 inches (10 to 21 cm) tall, and they are ready for field planting the fall following container planting. These seedlings are particularly suited for planting in remote areas because they are lightweight and easy to transport. Seedlings in deepots are also grown for a single season, while those in treepots are transplanted into larger containers and require 2 years to reach the desired size.

Acorn Collection and Storage. Acorns sown by Circuit Rider are generally collected close to the future planting site within the same watershed to ensure adaptation to local conditions. Collection sites are tracked by accession numbers and, for the more common oak species, collections are made at 20 to 25 different sites for a given year in Northern and Central California. Circuit Riders usually harvest acorns directly from trees, either by picking them from branches or by knocking them to the ground with poles. After discarding obviously defective acorns and sorting them by flotation, acorns are placed in small to medium resealable polyethylene bags containing a moist medium consisting of vermiculite or perlite, or a combination of the two. Acorns are mixed with a high volume of medium to maintain high acorn moisture during storage. The bags are then placed in a refrigerator at 40°F (4.4°C) until sowing in containers. If radicles become long and tangled during storage, they are trimmed prior to sowing. When planting in containers, acorns are sown with the pointed tip buried halfway at an angle of approximately 45 degrees and placed in a shadehouse to germinate. They are kept in partial shade during the summer to ensure that the containers don't dry out too quickly.

Tree of Life Nursery

The Tree of Life Nursery has been producing native California plants for more than two decades and claims to be the largest supplier of native plants in the state. Their grounds, located in San Juan Capistrano, include 30 acres of growing area with both shadehouses and greenhouses, and they maintain laboratory facilities for the propagation and testing of mycorrhizal plants and inoculum. They grow a wide variety of native oak species, including blue, valley, coast live, California black, canyon live, island (*Quercus tomentella* Engelm.), scrub (*Quercus berberidifolia* Liebm.), coastal scrub (*Quercus dumosa* Nutt.), and Engelmann oak. They are particularly well known for growing Engelmann oak seedlings since the nursery is located within the very narrow range of this species, and they have worked closely with conservation groups focusing on Engelmann oak restoration.

Acorn Storage and Sowing. The Tree of Life Nursery collects acorns from a variety of collection areas for most species, and records identifying the location of the seed source are maintained. Acorns are then put in water, with floaters discarded and sinkers placed in lugs or flats containing moist peat moss. After germination, radicles are pinched off, the acorns are sown in super cells, and the seedlings are grown for one growing season. Nursery manager Mike Evans feels that root pinching is beneficial since it promotes the early development of a more fibrous root system and improves the ratio of roots to shoots. The potting mix consists of 80 percent organic amendments, including bark products and peat, and 20 percent inorganic components, consisting of perlite, vermiculite, and sand. A slow-release, 18-6-12 fertilizer is incorporated into the potting mix prior to planting, and the seedlings are generally inoculated with an endomy-corrhizal fungi, VAM 80. This fungi is thought to enhance the ability of seedlings to take up nutrients following outplanting, thereby improving field performance.

Transplanting. After one growing season, seedlings are either sold or transplanted into larger containers. Many are planted in 1-gallon containers that promote the development of a much deeper root system, resulting in better growth and survival after outplanting. After 1 year in this size, some oak seedlings are sold, while the remainder are transplanted into 5-gallon containers. After one additional growing season, seedlings are either sold or transplanted to 15-gallon pots, the largest size grown by the nursery. At each stage of transplanting, excess roots are trimmed off prior to moving the seedlings to larger containers. Generally, the smaller seedling sizes are destined for revegetation plantings, while the larger sizes are for landscaping projects.

California Department of Forestry L. A. Moran Reforestation Center

The L. A. Moran Reforestation Center in Davis is the only container nursery operated by the California Department of Forestry and Fire Protection (CDF). Its primary mission is to sell tree and shrub seedlings to the public. While, historically, the main focus of the nursery has been to produce and sell commercial conifer species, there has been increased emphasis in recent years on growing native plants for restoration purposes. The nursery has produced native oak seedlings since 1987. Their primary species are blue and valley oaks, with lesser quantities of California black, coast live, canyon live, interior live, Engelmann, and Oregon white oaks. However, the species grown and number of seedlings produced depend largely on the availability of acorns, and during poor acorn years, the number of seedlings of a given oak species may be restricted. The nursery produces an average of approximately 5,000 oak seedlings annually and as many as 10,000 additional seedlings as contract requests.

Acorn Processing. CDF is particularly concerned with identifying the sources of all their acorns and only distributing seedlings from acorns that have been collected relatively near the planting area. Acorns are generally collected directly from the tree branches or knocked off trees with poles. They are upgraded by discarding obviously cracked or damaged ones, including those with multiple bore holes and uneven coloration. The CDF nursery then X-rays the seed lot, which provides an additional indication of quality. If the quality is good, no further treatment is done. If there are many empty acorns, the CDF nursery uses an air separator to cull them. After sorting, acorns are stored in plastic bags that are left slightly open at the top and refrigerated at 35°F (1.7°C) until planting.

Sowing. To prevent deterioration and premature germination, acorns are generally sown in early winter, preferably by mid-December. They are sown one per container on their side and covered with about ½ inch (1 cm) of coarse vermiculite. The containers are foil-covered, paper, plant sleeves that are 2½ by 2¼ by 12 inches (6 by 6 by 31 cm) and are open at the bottom to promote air pruning of the roots. A well-drained potting medium containing peat, bark, perlite, and vermiculite is used and a slow-release fertilizer is incorporated into the mix to promote the breakdown of the bark and to encourage initial root growth. Perlite is used as a top dressing to decrease drying. Following sowing, the containers are moved directly into a shadehouse where the acorns germinate. When germination appears complete, the empty containers are removed and the remainder consolidated. Regular irrigations from an overhead system usually commence in the spring and are designed to provide deep thorough soakings, with seedlings drying between each irrigation. A balanced fertilizer is added through irrigation water, but rates are kept low. The following winter, the seedlings are sized, graded, and made available for sale.

Bareroot Seedling Production

Few bareroot oak seedlings are produced in the state. However, the California Department of Forestry and Fire Protection Nursery at Magalia began growing and selling a limited number to the public about 10 years ago. To determine which cultural practices are most effective for bareroot production of blue oak seedlings, a study was initiated at the nursery in 1987 to compare several root pruning (drawing a blade through the soil 8 to 10 inches [21 to 26 cm] deep to cut off deep roots) and sowing treatments (Krelle and McCreary 1992).

Root Pruning

Undercutting roots is common in the production of commercially important oak species such as northern red oak in the East and Midwest (Johnson 1988). Results from the Magalia study indicated that it was essential to prune seedling roots in order to produce acceptable plants. If the roots were unpruned while in the nursery bed, they grew so deep that it was impos-

Recommended Procedures for Growing, Lifting, and Storing Rangeland Oak Seedlings in Bareroot Nurseries

- Sow acorns in nursery beds by the end of January at a density of no more than 12 to 14 per square foot (129 to 151/m^2).
- Undercut seedling roots in both May and August to inhibit taproot development and promote a fibrous root system.
- Lift seedlings no later than early February and place in cold storage, making sure roots stay moist.
- Store seedlings for up to 2 months, but avoid extended storage for late-lifted stock (see chapter 4).

Figure 8. These bareroot seedlings were field-planted in 1989, and many are now over 10 feet (3 m) tall.

sible to "lift," or remove, them from the nursery beds without damaging them. However, the timing of the pruning was critical. If pruning was done too early, before the roots had grown down at least 8 inches (21 cm), then it had little or no effect on root form. If pruning occurred too late in the season, after seedlings had produced fairly thick, deep, carrot-like roots, then so much of the roots were lost during pruning that the seedlings were severely damaged, and, in many cases, died.

Based on the results of these experiments, nursery manager Bill Krelle opted for both an early (May) and a late (August) pruning treatment to produce the best blue oak seedlings, with the second pruning approximately 2 inches (5 cm) deeper than the first. This study also found that seedlings from a late fall or midwinter sowing performed much better than those from an early spring sowing since late sowing apparently delayed germination and resulted in greatly reduced growth. In this trial, seedlings were grown for a single season at a density of 12 to 14 per square foot (129 to 151/m^2), though much lower bed densities are common for growing northern red oak (Schultz and Thompson 1997).

Lifting Dates and Storage

The 1987 Magalia study also evaluated different lifting dates and seedling storage treatments and found that bareroot blue oak seedlings could be lifted over a fairly wide interval, extending from early December to early February, without seriously affecting seedling quality. They could also be cold-stored for up to 2 months without damage, as long as the roots were not allowed to dry out. Seedlings from this trial (McCreary and Tecklin 1994b) have now been growing at the University of California Sierra Foothill Research and Extension Center for 10 years, and many are 10 to 15 feet (3.0 to 4.6 m) tall with basal diameters exceeding 2 inches (5 cm) (fig. 8).

Recommended Procedures for Vegetative Propagation

Vegetative propagation may be a desirable alternative to growing seedlings in containers or in bareroot nurseries because it offers the opportunity to produce uniform, genetically superior plants selected for traits such as disease or drought resistance. Another advantage is that this production method does not depend on acorns. As noted previously, acorns do not store well, and because acorn crops are so variable, restoration planning can be very difficult and seedlings unavailable when needed.

At present, however, no vegetatively propagated oak seedlings are commercially produced in California. Even for important eastern species, such as northern red oak, commercial vegetative propagation is uncommon, though there has been considerable research on it. The most widely tested method of vegetative propagation for oaks is with the use of rooted cuttings. While it is generally recognized that oaks are more difficult to root than many other woody species, it can be done. Most of the successes are attributed to combinations of using cuttings from young plants and providing growth regulators, moisture, and shade (Davis 1970; Zaczek, Heuser, and Steiner 1997). Isebrands and Crow (1985) successfully rooted softwood cuttings of 3-week-old northern red oak in a greenhouse, and Drew and Dirr (1989) found that cuttings from younger flushes (a period of stem elongation) rooted better than those from older flushes. Morgan (1979) also reported that the younger the oak, the greater the rooting success. In almost all trials, cuttings were treated with the hormone indoyl butyric acid (IBA) to stimulate rooting.

In vitro plantlet regeneration of several oak species has also been reported. Shoot cultures of English oak have been established and multiplied using original material from both juvenile seedlings and stump sprouts from mature trees (Vieitez, San-Jose, and Vieitez 1985). However, this approach is difficult and expensive, and it is unlikely that California oaks produced in this manner will be available in the near future.

Mycorrhizal Inoculation

Inoculating oak seedlings with mycorrhizal fungi has been reported to improve field performance after outplanting (Garrett et al. 1979; Anderson, Clark, and Marx 1983; Ruehle 1984; Dixon et al. 1981). This improvement is attributed to an increased capacity of the root system to take up moisture and nutrients. On sites in California where oaks were cleared decades ago and have remained treeless since, a lack of mycorrhizal inoculum could be a factor inhibiting natural oak regeneration. While a number of mycorrhizal species can be found in oak woodlands, there has been little evidence that artificially inoculating California oak seedlings, either before or after planting, significantly improves growth and survival. At the University of California Sierra Foothill Research and Extension Center, we compared valley oak seedlings inoculated with the broad spectrum and commercially available *Pisolithus tinctorius* mycorrhizae to uninoculated controls but could detect no subsequent improvement in field performance after outplanting.

However, in a trial that incorporated litter from under Engelmann oak trees (and presumably inoculum of native mycorrhizae) into planting spots with Engelmann oak seedlings and acorns, significant increases in a number of growth variables were reported (Scott and Pratini 1997). While it could not be proven definitively that mycorrhizae from the native soil conferred a growth advantage, it was concluded that this was likely. Berman and Bledsoe (1998) also added soils from valley oak riparian areas to growth media for valley oak seedlings grown in a greenhouse and found that the percent mycorrhizal infection and mycorrhizal diversity on the seedlings were increased more by transfer of oak forest and woodland soil than agricultural field soil. While the benefits of mycorrhizal inoculation for native California oak seedlings are not yet well documented, the Tree of Life Nursery regularly inoculates their oak seedlings, and its staff believes it confers a significant benefit after outplanting.

4

Seedling Planting, Maintenance, and Protection

Regeneration research in California during the past 12 years has indicated that successful oak establishment is dependent upon proper planting, maintenance, and protection. The greatest barriers to success are weed competition and animal damage. Regard-less of how well acorns are collected and processed or how well seedlings are grown and planted, if competing vegetation is not controlled and acorns and seedlings are not protected from damaging animals, chances for success are slim. Below are discussions of techniques and practices that can greatly enhance the prospects that outplanted acorns and seedlings will grow into saplings and trees.

Planting Rangeland Oak Seedlings

When to Plant Seedlings

As with date of sowing acorns directly in the field, the planting date for seedlings can influence subsequent field performance. The greatest problems arise from planting seedlings too late in the season. For blue and valley oaks, March is usually too late, and it is preferable for seedlings to be planted by the end of January. Bareroot blue oak seedlings lifted on several dates and stored for varying intervals performed well as long as they were not planted after early March (McCreary and Tecklin 1994b), and 1-year-old container seedlings planted in mid-December tended to grow more than those planted 6 or 12 weeks later (McCreary and Tecklin 1993b). In environments with low average annual rainfall and early onsets of spring and summer, these planting dates should be moved up even earlier.

Because both blue and valley oaks are able to grow roots during winter, early planting allows them to develop well-established root systems while the soil is still moist. In the Mediterranean climate of California, having such a root system is critical because there might be little or no rain for nearly 6 months, and the soil, especially near the surface, can become exceedingly dry. Seedlings planted late in the season may simply not have sufficient time to develop an adequate root system before soil conditions preclude further growth. It should be mentioned, however, that we have successfully planted seedlings of the 4-month-old stock type described in **Seedling Production in Containers** (see chapter 3) in March and even April. But, in all instances, the seedlings have been thoroughly watered at time of planting to ensure sufficient soil moisture for initial root growth.

How to Plant Seedlings

There are standard procedures for planting conifer seedlings (Schubert, Adams, and Richey 1975), and these apply to oaks as well. First, the seedlings should be maintained properly prior to planting, so that they are not injured. Seedling roots are particularly vulnerable and should not be allowed to dry out, heat up, or freeze, and care should be taken to make sure seedlings are not physically damaged by rough handling. It is also important to plant seedlings at the proper depth so that the ground line at planting is roughly similar to the seedling's ground line when it was growing in its container or bare-root nursery bed (fig. 9). The planting hole should be deep enough so that the roots do not turn up ("J-rooting") at the bottom of the hole. Finally, the soil should be suitably moist, not frozen, and any air pockets in the ground adjacent to the roots should be eliminated by gently compacting the soil, or irrigating thoroughly around the seedling immediately after planting.

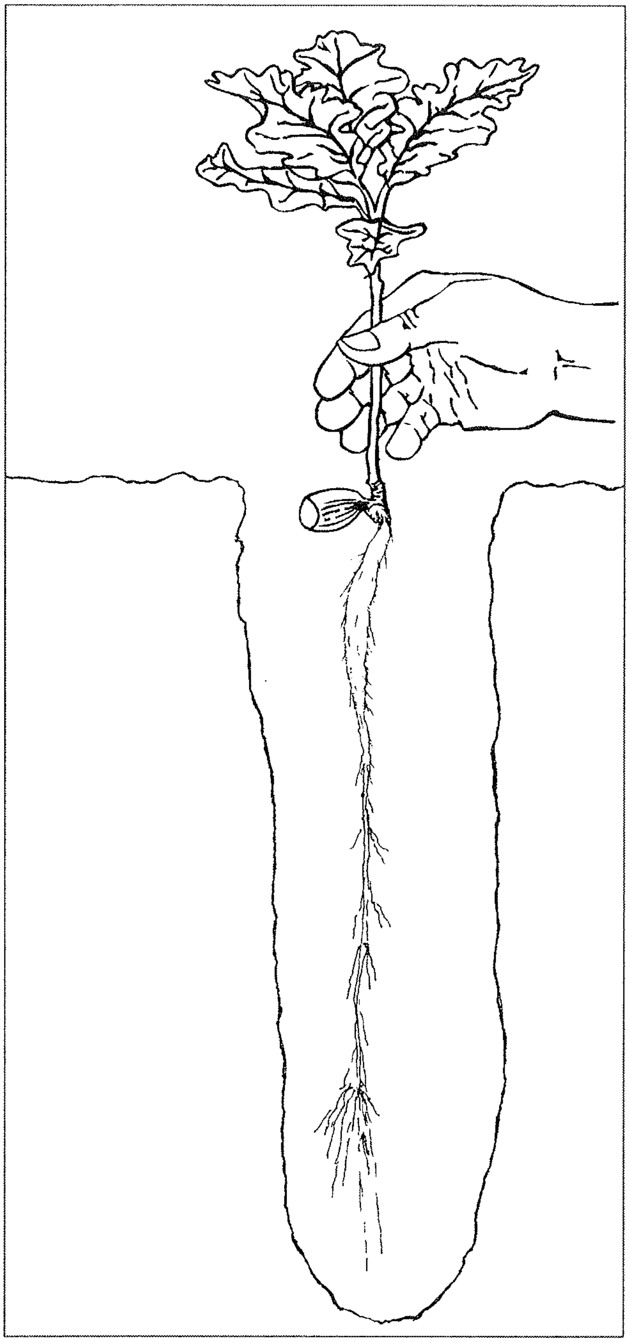

Figure 9. It is important to maintain the same ground line when outplanting oak seedlings.

There are a variety of tools that can be used to make holes prior to planting, including shovels, power augers, tiling spades, hoedads, and clamshell-type post-hole diggers. We have used the latter extensively at the University of California Sierra Foothill Research and Extension Center and have found that holes can be excavated fairly rapidly, as long as the soil is sufficiently moist and the ground is not too rocky or compacted. An additional benefit of post-hole diggers, compared with tools that create a slit in the ground, is that the holes created allow the root to initially have much more of a three dimensional configuration, which can be especially important when planting container seedlings that have a plug of soil and roots. Digging a hole with a post-hole digger also facilitates placement of fertilizer at the appropriate depth.

Auger Planting

Many of the hardwood rangelands in California have been grazed continuously for the past two centuries, compacting the soil in many locations. There are also areas underlaid with natural hard pack. Hard, compacted sites can make it difficult for oak roots, especially those of shallow-planted acorns, to penetrate downward. Augering planting spots (fig. 10) can greatly reduce the bulk density of the soil and make it much easier for the oak roots to grow downward. At SFREC, we evaluated three depths of augering (1, 2, and 3 ft [30, 60, and 90 cm]) and found that, compared to unaugered controls, all three depths improved the growth of surviving blue oak seedlings planted from acorns (McCreary 1995). However, we also found that the 3-foot augering had a negative side effect. In spite of efforts to compact the soil that we placed back in the holes for these deep-augered holes, the holes tended to subside several inches after the first heavy rains. In several instances, this caused acorns to become exposed, resulting in higher acorn depredation, probably from mice. As a consequence, overall mortality for this treatment was higher.

Figure 10. Tractor-mounted augers can be used to break through compacted soil.

We could also detect little difference between the three augering depths tested. We attributed this to the fact that most of the compaction was in the upper foot of the soil, and as long as this area was broken up, the oak roots had little trouble growing deeper. We therefore recommend either augering compacted soils prior to planting or excavating holes with a shovel or post-hole digger, but only to the depth required to penetrate the bottom of the compacted layer. It is important to auger well in advance of planting either acorns or seedlings so that the soil can settle thoroughly with natural rainfall. Finally, in wet, heavy soils, augering can result in a slick, smooth surface on the inside of the hole created. This can make it difficult for the oak roots to penetrate, and even slow water percolation so that the holes act like a pot. If holes become glazed from augering, use a shovel or tiling spade to rough up the sides of the hole before planting.

Selecting Microsites for Planting

Many areas targeted for oak regeneration contain a range of possible planting locations, or microsites, for individual seedlings. Even over short geographical distances, conditions at these planting sites can vary greatly. Some may be adjacent to rocks, logs, or stumps that provide natural protection and reduce direct solar radiation. Others may be close to gullies, swales, or even springs where soil moisture is greater. Still others may be far from obvious animal populations, as evidenced by gopher mounds or ground squirrel tunnels that can pose a threat to seedlings planted nearby. Finally, there is some evidence that certain shrubs may act as nurse plants for blue and valley oaks and promote establishment of seedlings planted near them (Callaway 1992). Because resources for plant restoration projects are generally limited, and it is too expensive to plant everywhere, it makes sense to choose microsites where seedlings will have the best chance to survive and grow. These may be difficult to determine, but insight can often be gained by looking at nearby areas where oaks are present and observing patterns where trees have become established naturally. In oak woodlands, south-facing, exposed ridges are generally less likely to have oaks than are north-facing slopes or drainages because soil conditions are much drier on southern aspects. And in grazed areas, oaks that have survived can often be found in locations that present some natural barrier to livestock and deer, such as rock outcrops. Mimicking such patterns in artificial regeneration efforts and choosing sites that afford some natural protection or better environmental conditions can often enhance success rates.

Planting Patterns

The number of acorns or seedlings to plant in a given area depends on how many oak trees are desired to grow there, as well as on attrition. Unfortunately, it is difficult to predict how many trees will be produced from plantings because a host of factors, including weather, animals, and competing vegetation, can influence survival. But following the steps described below on weed and animal control will help minimize mortality. Using these methods, it is not unreasonable to expect 70 to 80 percent, or higher, survival in many locales after the first 2 years.

The growth rates of seedlings also vary depending on species, site, and intensity of management. To predict the canopy cover after a given number of years, all of these factors need to be considered. A model of blue oak growth based upon the initial 10-year growth of a planting in 1987 (McCreary 1991) and stand structure models for this species developed by Standiford (1997) found that, under a high level of management (weed control for 3 years, protection from animals, fertilization), the canopy cover after 30 years would be 29 percent with 400 seedlings planted per acre (988/ha). With less intensive management (1 year of weed control, no protection), canopy cover over the same interval would be expected to be approximately 13 percent.

When planting, consider spacing seedlings or acorns in a naturalistic manner rather than in straight rows, using surrounding stands of oaks as a model. Also consider planting in small clumps or clusters, with some open areas between the clumps. Planting trees in clusters rather than with relatively uniform spacing can break up the landscape and provide more horizontal diversity of vegetation, which may benefit a wider range of wildlife.

Weed Competition

How Weeds Impact Oak Seedlings

Competition for Soil Moisture. The primary effect of competing vegetation on both planted and natural oak seedlings is a reduction in soil moisture available for uptake. In the Mediterranean climate of California, where there is often little precipitation from April to October, a lack of moisture in the soil can limit growth and affect survival. Because all plants growing in an area compete for the same limited amount of water, more competition means less moisture available for oak seedlings (fig. 11). Eliminating this competition by the methods described in this section means greater access to moisture and a greater chance for growth and survival for oak seedlings.

Drought Resistance. Oak seedlings in California have evolved a number of mechanisms to deal with limited moisture in the dry part of the year (Rundel 1980). Germinating acorns tend to produce large and deep root systems before they start to grow a shoot. As mentioned above, this growth pattern allows oak seedlings to reach deeper soil where more moisture is available longer. In a 1986 report, Matsuda and McBride found that during the first growing season, 73 percent of the dry weight of blue oak was allocated to belowground material. They also found that California oaks showed much greater root elongation and smaller leaf area to root weight ratios than Japanese oak species. Their conclusion was that the extensive root systems and small leaf areas of California oaks help seedlings survive under dry conditions (1989b). Momen et al. (1994) evaluated the water relations of planted and natural blue oak seedlings and concluded that they also "resist drought by osmotic adjustment, particularly when seedling water stress progresses slowly because of lack of severe, belowground competition from grasses." Under extremely

Recommended Procedures for Planting Rangeland Oaks

- Plant oak seedlings early in the growing season, soon after the first fall rains have saturated the soil; do not plant after early March unless irrigation is planned.
- Make sure seedlings are not frozen, allowed to dry out, or physically damaged before, during, or after planting.
- Plant seedlings at proper depth, making sure they are not J-rooted, and eliminate air pockets in soil adjacent to seedling roots.
- In hard, compacted soils, break up soil (using a shovel, auger, or post-hole digger) through the compacted zone prior to planting to promote deeper rooting. If planting holes are augered, make sure the sides of the holes are not glazed.
- Select microsites for planting that afford some natural protection and provide the most favorable growing conditions.
- Plant in a natural pattern, avoiding straight, evenly spaced rows.

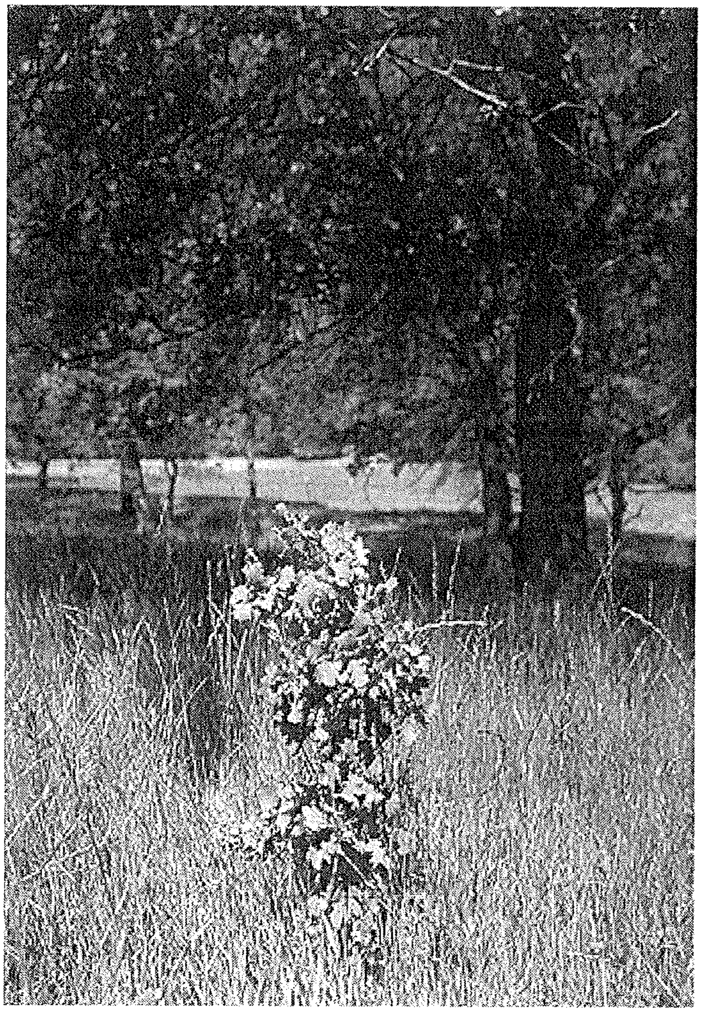

Figure 11. Natural, or volunteer, oak seedlings often face severe competition from dense annual plants.

Figure 12. Oak seedlings typically grow a deep taproot with relatively little lateral root branching.

harsh conditions, oak seedlings can also grow very slowly. Phillips et al. (1997) found that more than 10 percent of blue oak seedlings less than 1 foot (31 cm) tall in portions of the southern Sierra Nevada Foothills were more than 25 years old, even though there was no evidence of browsing.

Taproots. Most oaks initially produce a primary taproot and relatively little side branching (fig. 12). But do nursery production systems that prune this initial taproot, and, therefore, prevent normal root development, predispose seedlings to slow growth or even death after outplanting? We have tried to answer this question by observing roots of both planted and natural, or "volunteer," oak seedlings, as well by monitoring the root growth of acorns planted in root observation boxes. Our experience suggests that the initial taproot configuration may not last long in nature and is probably not critical for regeneration success. Roots growing downward in soil may encounter rocks or other impenetrable objects. Soil microorganisms can also attack the root tips. The result is the development of several taproots at the point of injury or obstruction. These multiple roots continue growing downward and appear to function similarly to single taproots. In one study, we planted pregerminated, blue oak acorns that had intact radicles (and were, therefore, presumably predisposed to a single taproot configuration) alongside acorns that had radicles severed at approximately ½ inch (1 cm) to promote the development of multiple taproots. While this treatment clearly affected root morphology, we could detect no subsequent effect on field growth or survival (McCreary 1996). Koukoura and Menke (1994) found that pinching the roots of blue oak seedlings resulted in faster root growth but did not affect total root length and dry mass.

Competition for Nutrients and Light. In addition to vying for a limited amount of soil moisture, forbs and grasses also compete with oak seedlings for nutrients and light. Although these factors are generally not as important as moisture competition, in certain instances, such competition can severely impact oak seedlings.

Recommended Weed Control Procedures

- Select method of weed control (herbicides, physical weed removal, or mulching) based on environmental, fiscal, and philosophical considerations.
- Maintain a weed-free circle that is 4 feet (1.2 m) in diameter around individual seedlings or acorns for at least 2 to 3 years after planting; if using herbicides to control weeds, remove weeds in circle with a diameter of 6 feet (1.8 m).
- Initiate annual weed control by early spring to ensure that weeds do not become established and deplete soil moisture before oak roots can penetrate downward.
- Visit planting sites at least twice annually to remove both early- and late-season weeds and weeds that may have grown through mulch.
- If using postemergent herbicides, make sure that chemicals do not come in contact with foliage or the expanding buds of seedlings.
- After weed control is discontinued, visit plantings regularly to make sure vole populations and damage to seedlings have not increased. If increases are observed, remove thatch.

For example, regardless of moisture availability, small oak seedlings growing in dense competition with forbs and grasses may simply not receive sufficient light for growth.

Secondary Effects of Weeds

In addition to their primary competitive impacts, the undesirable dense growth of annual grasses and other exotics we call *weeds* can also have significant effects on oak seedlings by providing a favorable habitat for animals that can damage them. For instance, large amounts of dead annual grasses, or thatch, can provide an ideal habitat for voles or meadow mice *(Microtus californicus)*. The fecundity of these animals is high, and populations can increase dramatically when weeds are neither grazed nor artificially controlled. The result can be serious damage to oak seedlings. At the University of California Sierra Foothill Research and Extension Center, we have observed oak saplings that are 8 feet (2.4 m) tall and girdled half way up the stem when weed control was discontinued and thatch levels rose, providing ideal vole habitat (see **Length of Time for Weed Control**, below). Removing weeds even in relatively small areas around seedlings can greatly reduce vole damage (Davies and Pepper 1989; Tecklin and McCreary 1993).

Grasshopper herbivory is also affected by the amount of herbaceous vegetation in proximity to seedlings. We have successfully reduced grasshopper damage to blue and valley oaks by spraying herbicides and mowing grassy areas inside planting zones, thus reducing late-season green weeds that are attractive for grasshoppers. This usually requires treatment of the entire planting area (as well as a perimeter), rather than treating small areas around individual seedlings since grasshoppers can readily fly short distances from treated to untreated areas.

Weed Control

As indicated above, controlling weeds around planted acorns or seedlings is essential because direct weed competition and the habitat created by weeds can make it very difficult for oak seedlings to survive and grow. Studies have repeatedly shown that weed control can greatly enhance the field performance of blue and valley oaks (Adams et al. 1992; Adams, Sands, and McHenry 1997; McCreary and Tecklin 1997). There are a variety of methods that can be used to eradicate weeds. The actual procedure or technique chosen may depend on many variables, including equipment or materials available, oak species planted (deciduous or evergreen), and even a grower's philosophical orientation. For instance, some people prefer not to use herbicides of any sort because of concerns about health and environmental contamination. Whichever methods are chosen, weed control greatly improves the chances for the success of oak plantings.

Herbicides. These are generally the cheapest, easiest, and most effective method of eliminating weeds. While herbicides are routinely used in California around oak seedlings, there have been no large-scale trials to determine which chemicals are most effective for which weed species and soil types and which cause the least injury to nontarget plants. The most common chemical currently used is probably glyphosate. This is a broad-spectrum, postemergent herbicide that kills grasses and forbs. It is considered to be safer than many herbicides and carries a "caution" rating on the label, meaning that it is an unrestricted chemical. It breaks down rapidly and has no residual activity in the soil. It should not be sprayed on the foliage of oak leaves, however, especially the new growth and initial shoots emerging from planted acorns, because glyphosate might seriously damage or kill seedlings.

We have sprayed glyphosate directly over the tops of deciduous oaks in the winter when they have no leaves, but, even in this situation, a small percentage of seedlings demonstrated signs of herbicide injury. Seedlings appear to be more vulnerable to this type of damage when buds are swelling in the early spring. Even when seedlings are dormant, it is safest to avoid chemical contact with twigs or buds. For very small seedlings, individual plants can be covered with anything from paper cups to 1-gallon or larger containers. Alternatively, spray can be applied directionally away from plants, but it is important that the air be still so there is little chance of drift onto the seedlings. It is also possible to protect small- to medium-sized seedlings by placing a section of stovepipe over them (fig. 13) while spraying, being careful not to allow any drift to enter the open top. Pieces of cardboard or a similar shield can also be used to protect one side of a plant, rotating the cardboard around to the opposite side when spraying weeds on that side, as long as the side that has had contact with the herbicide does not touch the seedlings.

Spraying glyphosate early in the spring is advantageous from a soil moisture point of view because killing competing plants when they are small and have not yet seriously depleted soil moisture means that there will be more water available for the oak seedlings. However, one problem with foliage-active (as opposed to soil-active or pre-emergent) herbicides, such as glyphosate, is that they only affect the plants that are present when the chemical is applied. On California rangelands, there are many annual plants, mainly from the family Asteraceae, such as yellow starthistle *(Centaurea solstitialis),* that usually germinate quite late in the season and are not present during early-season applications. As a result, there can be a whole new contingent of plants competing with oak seedlings by late spring. If left untreated, these plants can create serious competition problems. We, therefore, recommend an additional weed treatment in May to eliminate these late-germinating plants.

Physical Weed Removal. Several years ago, we initiated an experiment to compare various sizes of weed-free areas around young blue oak seedlings (McCreary and Tecklin 1997). Weed removal was provided by using a hoe to scrape the surface vegetation, leaving only bare soil (fig. 14). This treatment was applied in early spring and not only removed weeds that were currently growing, but greatly reduced the seed bank in the upper inch or so of soil. This essentially eliminated competition in the early part of the growing season. Unfortunately, later in the spring, numerous weeds returned and a repeat scalping was necessary to keep the areas bare. All scalping treatments resulted in significantly better field performance than the control, and the larger the weed-free circles, the greater the subsequent seedling growth. However, it was extremely difficult and time consuming to scalp a 6-foot (1.8-m) diameter circle around each seedling. Scalping also becomes even more difficult in rocky or dry soil. Therefore, we can only recommend scalping when it is done on a small scale.

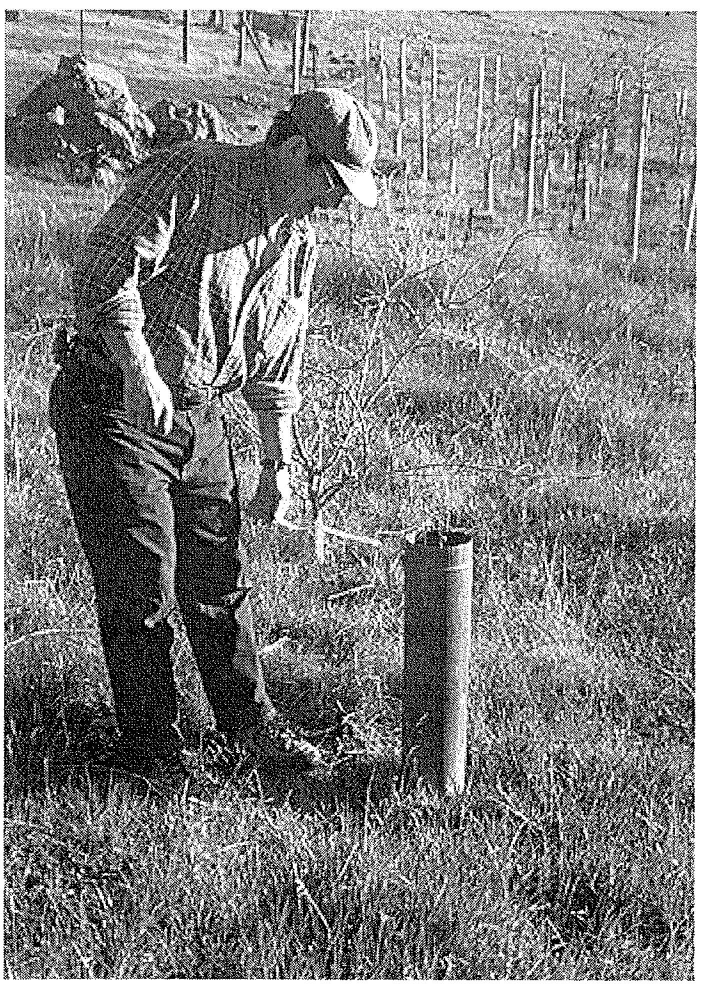

Figure 13. A stovepipe can be placed over oak seedlings to protect them while spraying weeds with postemergent herbicides.

We have also eliminated weeds around oaks late in the season using lawn mowers and weed-eaters. These treatments are not generally recommended because they only remove the top of the plants without killing them. If done early in the growing season, the plants will grow back rapidly and this treatment has little effect. It may even cause an increase in soil moisture loss as vigorous new growth following mowing, especially of grasses, can increase water use (Williamson 1992). However, if mowing is done in early or mid summer when most annuals have stopped growing and have turned brown, it can improve access and remove some of the habitat favorable to damaging animals, such as voles. In these conditions, the plants are not competing seriously with oak seedlings (except, perhaps, for light), but they are still providing habitat. Cutting weeds back may, therefore, reduce the potential for future animal damage. Cultivation is another technique for eliminating weeds but generally requires large equipment and multiple applications.

Figure 14. A hoe was used to remove ground vegetation from around this planted seedling, resulting in better field performance.

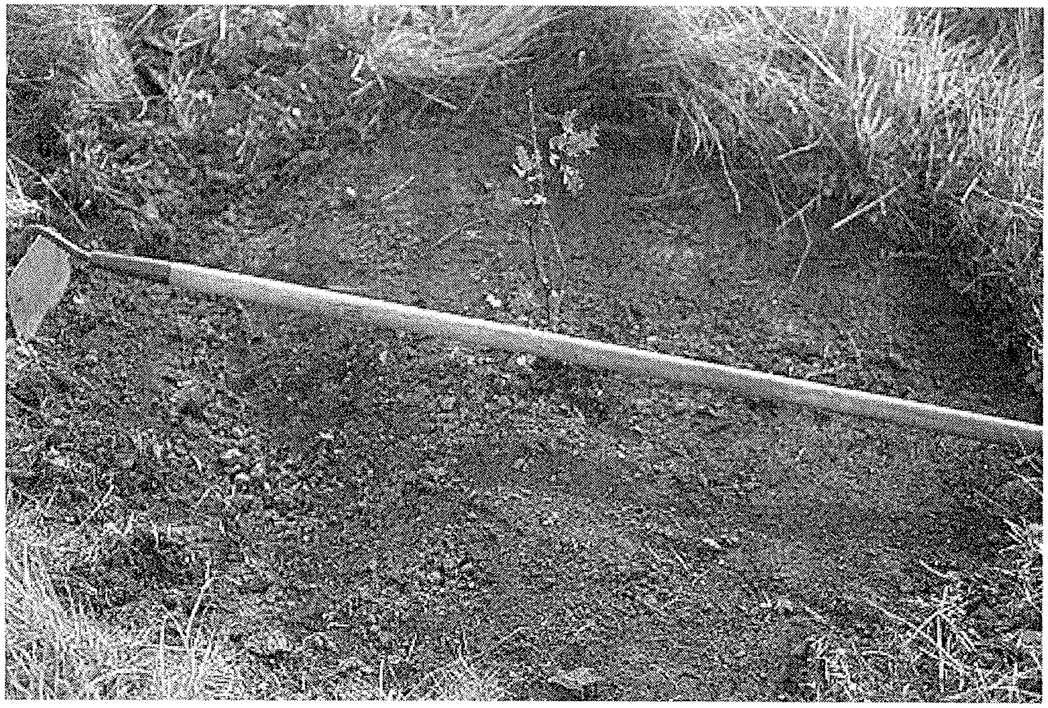

Figure 15. Organic mulches, such as bark chips, can effectively suppress weeds and reduce surface evaporation.

Mulches. There are a variety of organic and inorganic materials that can be used as mulches around young oaks. All of these materials tend to suppress weeds by physically covering them, thereby eliminating the light necessary for photosynthesis and growth. Organic materials include straw, wood chips, and compost (fig. 15). Plastic products are also commonly used, including those that are opaque but porous, allowing moisture to pass through but keeping light out. Mulches also conserve soil moisture by reducing evaporation from the soil surface, resulting in more moisture for the oak seedlings. Organic mulches can, over the long term, improve soil structure. As mulching materials break down and are incorporated into the soil, they tend to reduce soil bulk density, increase percolation, and improve the nutritional status of the soil.

It may be difficult to effectively suppress dense weeds that are already on-site using mulch alone unless the weeds are dealt with first. In these instances, it is often necessary to physically remove weeds before mulching, or to spray herbicides before putting the mulch in place, which reduces the likelihood that weeds will subsequently grow up through the mulch.

A study evaluating a variety of mulches, including black plastic, paper, and hay, on four oak species in the southern United States found that all of these materials positively affected growth for all species studied (Adams 1997). Adams, Sands, and McHenry (1997) compared impervious and porous plastic mulches on outplanted blue oak seedlings at the University of California's Hopland and Sierra Research and Extension Centers and found that both types of mulches significantly improved performance. Bernhardt and Swiecki (1991) also evaluated both organic mulch and polypropylene landscape fabric on valley oak plantings and found that both significantly increased growth. Circuit Rider Productions recommends installing a 3-foot-by-3-foot (91-by-91-cm) square of woven polypropylene fabric, secured with 6-inch (15-cm), heavy-gauge wire staples, around plantings to lessen competition for moisture and nutrients (Bush and Thompson 1990).

A problem with all mulches is that they do not last forever. Plastics tend to become brittle and photodegrade, while organic materials gradually decompose. Over time, weeds tend to grow through holes in the plastic or through shallow places in the organic mulch. For maximum benefit, these weeds should be regularly removed. In general, mulches are more expensive than herbicides and often require considerable upkeep and maintenance. As such, they are probably best suited for small plantings that can be managed intensively.

Area of Treatment. We have found that from a practical standpoint, circles with diameters of 4 feet (1.2 m) around individual seedlings are a good compromise between ease of application and effectiveness. While we found that even larger circles (6 ft [1.8 m]) promoted slightly greater growth (McCreary and Tecklin 1997), larger weed-free areas are considerably more difficult and expensive to provide (except with herbicides) and do not appear to be worth the extra effort and expense.

Length of Time for Weed Control. Determining when seedlings are fully established and need no further protection or maintenance involves site-specific judgments. It is, therefore, difficult to make generalizations about how long areas around oak plantings should be kept weed-free. This depends on the severity of the competition, the environmental conditions at the site, the growth rate of the seedlings, and the potential for animal damage once the weed control ceases. While we generally recommend a minimum of 2 to 3 years of weed control after planting, in some cases this may not be long enough. Although this interval may be adequate from a soil-moisture standpoint, it may not be adequate from an animal-damage standpoint unless other steps are taken to protect oak seedlings from animal damage (see **Treeshelters**, below).

Animal Damage and Control

Those involved in oak restoration projects know that there are many animals that eat or otherwise damage acorns and small oak seedlings. Damage from animals is not limited to artificially generated seedlings. An examination of natural seedlings often reveals shoot browsing, bark stripping, defoliation, and root clipping. Sometimes it seems remarkable that any oak seedlings are able to survive given the overabundance of damaging factors they must contend with in order to grow into trees.

Animals That Damage Acorns and Seedlings

Livestock. Both sheep and cattle browse young oak seedlings. In addition, both animals eagerly seek out acorns on the ground. The severity of browsing damage to young oak seedlings is related to the intensity of grazing (fig. 16). In pastures that are used rarely and for relatively short intervals, some oak seedlings may escape damage, especially if there is an abundance of other plants to eat. In intensively grazed pastures,

Figure 16. Cattle often graze in oak woodlands and can inhibit both natural and artificial regeneration.

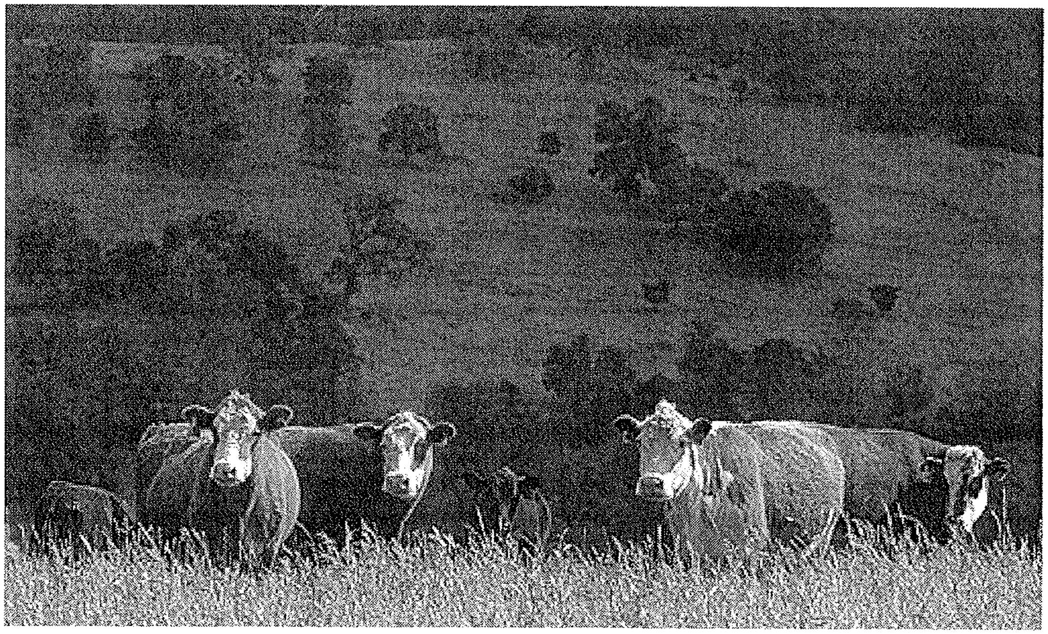

Figure 17. Oak seedlings can be stunted from the repeated browsing of deer and cattle.

unprotected oak seedlings have little chance of escaping injury. Repeated browsing can keep plants stunted for years, even decades (fig. 17).

In addition to browsing young oaks and eating acorns, large-hoofed animals, such as cattle, can also cause damage to small oaks by trampling them. Hall et al. (1992) found that, in confined pastures, trampling damage from cattle accounted for nearly 15 percent of total damage to blue oak seedlings. This same study also evaluated the extent of damage to planted oak seedlings at different times of the year. Not surprisingly, browsing damage was greatest for deciduous blue oaks in the spring and summer when the plants were fully leafed out and other green vegetation was scarce, and was least in the winter when seedlings were bare. The timing and intensity of grazing can, therefore, influence the extent of damage to unprotected oaks in grazed pastures.

Deer. A common species of deer on hardwood rangelands in California is mule deer *(Odocoileus hemionus Californicus).* The extent of their herbivory on both natural and planted oak seedlings varies greatly by site. In areas where deer are migratory and only pass through briefly at certain times of the year, damage will likely be minor. While annoying, such damage may be acceptable and not require protection. Such is the case at the University of California Sierra Foothill Research and Extension Center, where oak shoots are occasionally clipped off. However, in areas with resident deer herds, damage can be far greater (fig. 18). At the University of California Hopland Research and Extension Center in Mendocino County, deer browsing from a resident population precludes any successful attempt at artificially regenerating oaks without effective protection from these animals. Even oak stump sprouts there are clipped back to the trunk soon after they emerge.

In certain areas, repeated browsing can create bush-like plants that survive for decades. Griffin (1971) reported that it can take more than 20 years in a favorable habitat for coast live oak seedlings to grow above the reach of deer. At the Hastings Reserve in Carmel, White (1966) reported that only 12 percent of 154 oak seedlings were unbrowsed by deer and concluded that deer may be an important factor limiting seedling establishment (fig.19).

Rodents. Several rodents can seriously hamper oak restoration efforts. In a study evaluating various factors affecting survivorship of blue oak, Davis et al. (1991) stated that rodents were the most important predators of both acorns and seedlings. In blue and valley oak plantings at SFREC, the animals that have been the most troublesome are meadow mice, or voles (Tecklin and McCreary 1993), which thrive there in a dense cover of ground vegetation (fig. 20).

Acorns can also constitute a sizable portion of the diet of western gray *(Scirius griseus)* and California ground squirrels at certain times of the year (McDonald 1990), and these animals can destroy unprotected acorn plantings. Adams et al. (1987) reported that more than 5,000 blue and valley oak acorns were dug up at a planting in Madera County, presumably by ground squirrels. Deer mice (*Peromyscus* spp.) also eat acorns that are exposed or planted very shallow.

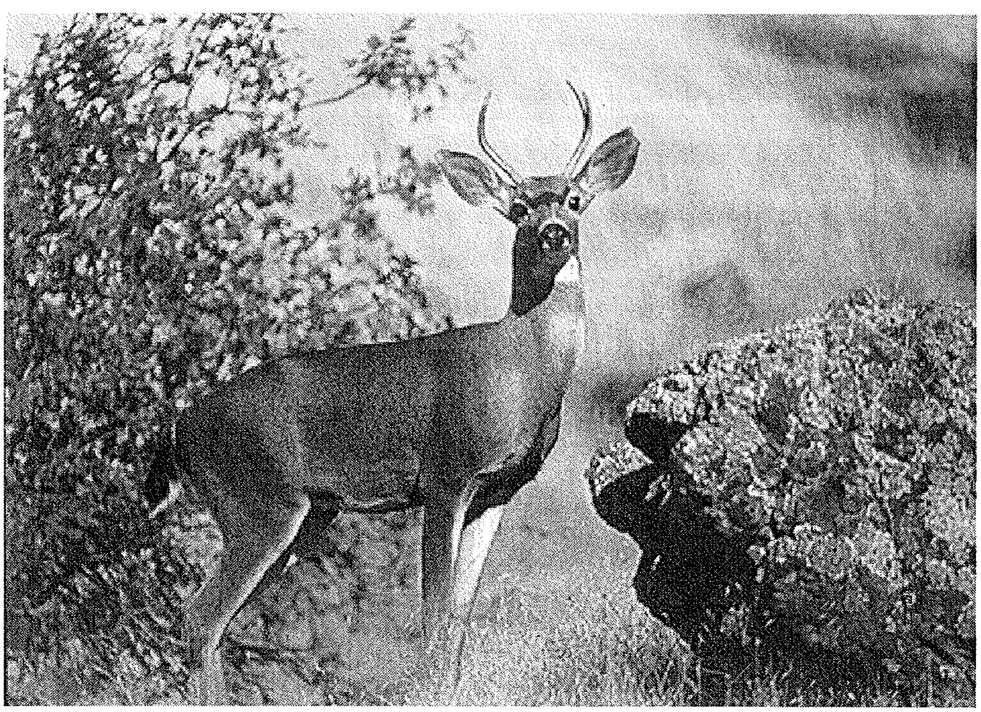

Figure 18. Many deer live among California's oaks, feeding on seedlings and other plants.

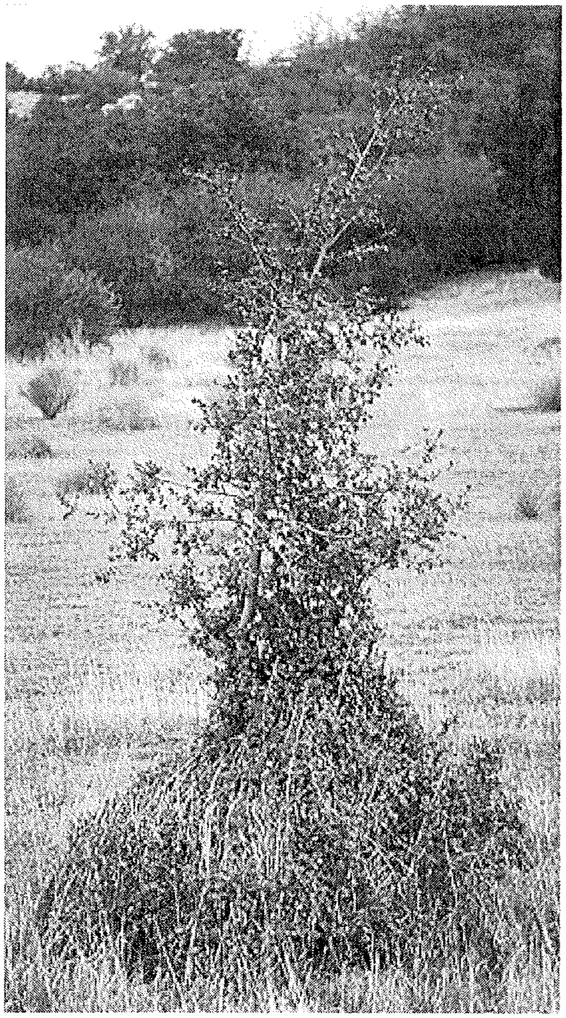

Figure 19. This oak was only able to release and elongate a dominant leader when the oak bush became so large that deer could no longer reach in and clip off shoots near the center.

Figure 20. This dense patch of dead grass and forbs, or thatch, is ideal vole habitat.

Pocket gophers *(Thomomys bottae)* constitute a serious pest in many oak plantings because they clip roots below the soil surface. In a study at the Hastings Reserve in Carmel in the early 1970s, Griffin (1971) noted that pocket gophers ate about 250 one-year-old seedlings in a woodland plot. Damage is not limited to newly planted seedlings, as gophers can kill oaks several years old, and also eat acorns (Griffin 1976). Gopher populations vary greatly by area and, in some locations, gophers are not a major concern. Where they are a problem, modifying the habitat can reduce populations and damage. However, this generally means treating entire areas and removing most or all of the surface vegetation. Gophers can also be effectively controlled by baiting with poisoned grain (see **Repellents and Baits**, below).

Insects. The primary insect damaging oak plantings at the University of California Sierra Foothill Research and Extension Center is the grasshopper, and in particular the species *Melanoplus devastator* (McCreary and Tecklin 1994a). As with many pests, populations fluctuate greatly from year to year, as well as over relatively short geographical distances. Even within the SFREC, we have observed large differences in the number of grasshoppers present within just a few hundred yards. Most commonly, populations seem to peak in late July and August. The cycle begins as eggs laid the previous fall hatch in the spring. Heavy rainfall years tend to promote the development and survival of large numbers because grasshoppers thrive in the abundant grass present in uncultivated areas. During years when populations are high, a single oak seedling can be covered with dozens of grasshoppers (fig. 21). During such outbreaks, almost all of the foliage on every unprotected seedling can be consumed. After the foliage is gone, the bark on seedlings is often stripped, and, in some cases, the seedling is completely girdled, killing the top. There are several other foliage-eating insects that also occasionally damage seedlings, but the injury is generally localized and not extensive.

The most common insect pests of California oak acorns are the filbert worm *(Melissopus latiferreanus)*

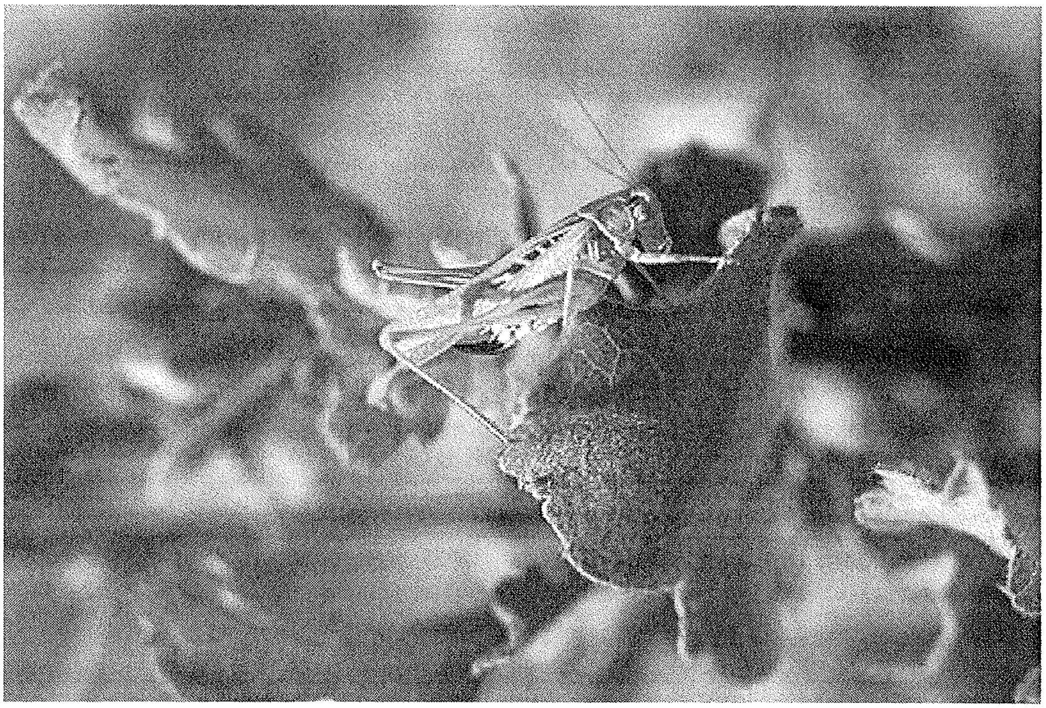

Figure 21. Grasshopper populations can explode during favorable conditions, and large numbers feed directly on oak seedlings.

and filbert weevils (*Curculio* spp.). The adults of the filbert worm lay their eggs on the surface of immature acorns, and, when the larvae hatch, they bore into the acorns. Adult filbert weevils penetrate the acorn skin or pericarp with their ovipositor and lay their eggs inside the acorns. As the larvae of both species grow, they feed on the cotyledons. Generally, the eggs are laid near the acorn cap and away from the pointed end of the acorn where the embryo is located. The larvae often emerge from the acorns during storage and accumulate in the bottom of bags or containers. Where there are multiple larvae in a single acorn, damage can be extensive. Griffin (1980) reported that over an 8-year period 21 percent of the valley acorns that dropped into collection traps were clearly nonviable due to insect damage, mainly from filbert weevils. However, even when much of the cotyledon is consumed, as long as the embryo is intact, the acorn can still germinate although there is less stored food available for initial root growth. The mature larvae usually chew their way through the shell of the acorn after the acorns drop to the ground in the fall (Brown and Eads 1965). In addition to the direct damage that larvae cause, their entrance and exit holes can also provide a site of entry for other pathogens that affect acorns (Swiecki, Bernhardt, and Arnold 1991).

A comprehensive listing of diseases and arthropods that affect native California oaks is contained in a host index database called CODA that was developed by Swiecki, Bernhardt, and Arnold (1997). CODA contains information on 45 native and cultivated oak species in California, 1,259 agents that affect these oaks, and 320 references that describe these interactions. It also contains information on 2,619 individual interactions between oaks and biotic or abiotic agents. It can be downloaded for free at http://www.phytosphere.com.

Protecting Rangeland Oaks from Animals

Without protection from animals, oak plantings often stand little chance of survival. However, the type of protection necessary depends on the type of damaging animals present. In some situations, large herbivores may be the primary species of concern, while in others, small insects may be the only threat. Below are descriptions of several general categories of animal protectors that have been used and some discussion about which animal pests they are most effective against.

Fences and Large Cages. It is estimated that over 80 percent of the hardwood rangelands in the state are privately owned (Bolsinger 1988). The primary economic use on many of these lands is livestock grazing. Because both cattle and sheep browse young oaks, it is often necessary to protect plants from them. Fences are obviously used to control livestock access to certain areas and can be built around oak plantings to keep animals out. But fences are not only costly to install and maintain, but if they exclude livestock from large areas, then these areas are removed from livestock production. If deer are a problem, higher and more costly fences are needed. Fences alone have not proven to be effective in promoting natural oak regeneration or in protecting artificial regeneration, except in small research exclosures with thorough weed control. This is because there are usually other animals, such as rodents and insects, that damage young oaks, even if livestock and deer are excluded.

However, in instances where deer and livestock are the only threats, fences may be effective. In these situations, it is important to weigh the costs of installing and maintaining fences against the costs of other types of protection. In England, the costs of fences were compared to the costs of protecting individual seedlings with treeshelters (see **Treeshelters**, below). It was concluded that if 450 trees per acre (1,112/ha) were planted, fences would only be cost-effective if more than 2 acres (0.81 ha) needed to be protected (Vickers 1999). However, this model did not consider the lost revenue from deferred grazing while fences excluded livestock.

Several types of small cages have also been used to keep livestock and deer away from individual oak seedlings or groups of seedlings. The simplest is a square exclosure, approximately 5 feet (1.5 m) per side, with metal fence posts at the corners and field fencing on the perimeter (fig. 22). This will effectively keep out livestock and deer since the protected area is too small to allow deer to jump inside. However, the cost is high, approximately $8 for four new fence posts and more for the field fencing and labor. In time, stock may also push the fencing over in efforts to reach young trees.

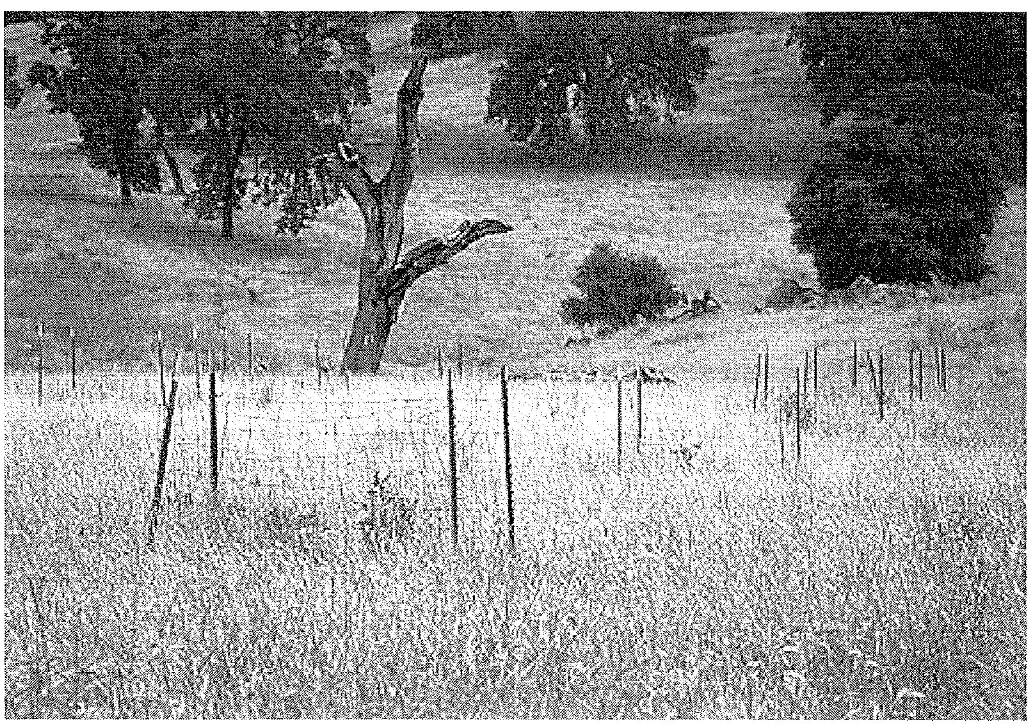

Figure 22. These exclosures, built with metal t posts and field fencing, effectively keep out deer and cattle.

Another type of cage using metal posts and field fencing has been described by Bernhardt and Swiecki (1991; 1997) and nicknamed a *vaca* cage (*vaca* is Spanish for *cow*). This is a circular structure approximately 4 feet (1.2 m) tall and 1½ feet (.5 m) in diameter, constructed from galvanized 12-gauge wire fencing with welded 2-by-4-inch (5-by-10-cm) mesh (fig. 23). The cage is secured to the ground with a t post and a 3-foot (.9-m) length of steel reinforcing bar. Materials costs per cage were $8 to $10 in 1997. Vaca cages are effective against deer and cattle although they do require periodic inspection and maintenance. They can be assembled and installed in about 12 minutes.

Screen Cages and the Collar-and-Screen Device. In oak regeneration studies initiated at the University of California Sierra Foothill Research and Extension Center in the late 1980s, seedlings were covered with cages made of aluminum window screen (McCreary 1989). These were constructed by cutting pieces of the screen into squares approximately 18 inches (46 cm) per side. These were then rolled into cylinders, folded closed at the top, and stapled to wooden stakes. The cylinders were placed over seedlings after field planting, and the stake was pounded into the ground (fig. 24).

These screen-cylinder cages cost about $1 each, plus labor, to construct. They were effective in preventing deer browsing, rabbit clipping, and grasshopper damage, but were worthless in pastures grazed by cattle since the ani-

Figure 23. This vaca cage costs approximately $8 to build and consists of a single t post, a 3-foot piece of rebar, and 5 feet of field fencing.

Figure 24. Tubes of aluminum window screen were initially used in oak regeneration trials at the SFREC.

Figure 25. When seedling growth reaches the top of aluminum screen cages, the screen should be opened to allow growth to progress normally.

Animals That Commonly Damage or Kill Rangeland Oak Seedlings and Recommended Seedling Protection

- Livestock, including cattle and sheep, eat oak foliage and consume acorns. In grazed pastures, seedlings must be protected, or they have little chance of growing. Fences can be used to keep livestock out of planting areas, but often other animals still damage plants. Treeshelters (see **Treeshelters**, below) secured to heavy metal posts can protect individual seedlings in moderately grazed areas.
- Deer browse seedlings and consume acorns. Damage is usually greatest when a resident herd is present. Planted areas can be fenced, or individual seedlings can be covered with treeshelters, screen cages, or seedling protection tubes.
- Voles, or meadow mice, strip bark from seedlings and saplings and can girdle and kill oaks. They thrive in dense grass or thatch, and populations can increase explosively. Damage levels can be greatly reduced by keeping the area within 2 feet (.6 m) of oaks free of vegetation.
- Pocket gophers commonly clip roots below the ground and can kill oak seedlings that are several years old. Seedling roots can be protected with hardwire cloth, aluminum window screen, or root guards, but material must degrade or be removed to ensure roots are not damaged as plants grow larger. Damage can be reduced by eliminating ground vegetation. In small areas, gophers can be effectively controlled by baiting.
- Ground squirrels clip seedlings and dig up acorns. High populations are usually evident by extensive mounds, holes, and burrows. Planting near such areas should be avoided.
- Grasshoppers eat foliage, and their damage is usually greatest in midsummer to late summer. Populations can fluctuate greatly from year to year, increasing dramatically during outbreak years. At these times, damage can be reduced by keeping the area where the oaks are planted free of ground vegetation.

mals easily knocked over and trampled them. The screens also presented another problem. As the seedlings grew taller, it was necessary to open them up, again making the tops of the seedlings vulnerable (fig. 25). If opening-up was delayed, the seedling became confined and deformed, a condition they do not soon recover from. In addition, insects and rodents could get underneath the screens if they were not buried or stapled down.

A modification of the screen cylinder method developed at the University of California, Davis, and refined by the Pacific Gas and Electric Company and Circuit Rider Productions (Bush and Thompson 1989) is the collar and screen. This consists, first, of a 1-quart (.95-L), plastic, yogurt or cottage cheese container with the bottom cut out. A square of aluminum screen is then wrapped around the plastic container and secured with wire and folded over at the top. The whole device is then placed over the seedling or direct-sown acorn with the plastic container sunk in the ground. This plastic container is believed to afford some protection against gophers (at least for shallow roots) and, if the plants are watered, creates a small, artificial reservoir. As long as plastic containers are available, this device is probably easier to assemble and less expensive than a screen cage.

Seedling Protection Tubes. Several manufacturers make seedling protection tubes from rigid plastic mesh (fig. 26). They can be purchased in lengths from 18 to 36 inches (.5 to .9 m) and are relatively inexpensive, with the 36-inch (.9-m) tubes costing about 28¢ each. They are usually secured to the ground with lath or bamboo stakes. They are not only reasonably effective in protecting against deer damage but also afford protection against rabbits. However, since the mesh is fairly wide, it is very easy for small animals, such as grasshoppers and even voles, to pass through, especially near the ground. As seedling shoots grow through the sides of the mesh (which is very common), the exposed portion is also vulnerable to browsing. Finally, these devices do not offer much protection in pastures grazed by cattle since they are easily uprooted or knocked over. Solid tubes called treeshelters were developed, in part, to overcome this limitation (see **Treeshelters**, below).

Underground Protection. As mentioned above, gophers and ground squirrels can be very troublesome in certain planting locations. In these situations, either the animals must be eliminated or the oak seedlings protected from them. Physical barriers have been successfully used to keep animals away from oak seedling roots. Plumb and Hannah (1991) reported that ¼-inch (6.5-mm) hardwire cloth buried 12 inches (31 cm) in

Figure 26. This seedling protection tube of rigid plastic mesh guards seedlings from deer and rabbits but not from grasshoppers or cattle.

the ground afforded some protection although they were concerned with the cost ($1 per seed spot) and the fact that these devices could restrict root growth as seedlings became larger. Adams and Weitkamp (1992) found that thin tubes of aluminum screening placed in the ground around seedling roots significantly reduced gopher damage. A metal mesh basket called "root guard" comes in several sizes and is designed to protect plant roots from gophers (see appendix B for source information).

Repellents and Baits. Some animals can be eliminated or controlled with poisons or baits. For gophers, probes can be used to place poisoned grain in underground tunnels. For large areas, however, this may not be practical. Also, baited areas must be regularly checked for evidence that gophers may have returned (distinctive C-shaped mounds will be present), and baiting repeated if necessary. Clearly, it is critical that no nontarget animals have access to the bait and that all pesticide labels be carefully adhered to when using any pesticide products.

The movement of grasshoppers into research plots from adjacent grassy areas can also be reduced using poisoned bait. A thin line of bait containing an insecticide can be placed around the perimeter of the oak planting area. The grasshoppers consume the bait as they move toward the plot and die before they reach the seedlings. This treatment has proven moderately effective at the University of California Sierra Foothill Research and Extension Center.

Habitat Modification. As mentioned earlier, animals require specific habitats to live and reproduce. If the habitat is significantly altered such that it is no longer suitable for their needs, the animals will leave or die. This knowledge of habitat requirements and preferences can be used to reduce or eliminate impacts from certain animals. The most effective way we have found to control voles, for instance, is to eliminate grass and forbs from an area. Even eliminating weeds in 4-foot (1.2-m) diameter circles around individual seedlings seems to provide a sufficient barrier that these animals are generally reluctant to cross, presumably because of predatory threats from hawks, owls, and other animals. Removing grasses and forbs in oak planting areas also helps to reduce grasshopper damage and has been used successfully to control pocket gophers in conifer plantations (Engeman et al. 1995).

Treeshelters

Treeshelters are individual, translucent, plastic protectors that fit over seedlings. Most are made from twin-wall polypropylene although some are made from single, flat sheets that are assembled on-site. Treeshelters were initially developed and tested in England 20 years ago (Tuley 1983; 1985). By 1984, over one million treeshelters were commercially manufactured and sold there. Although the number sold in England today is probably less, in 1991 it was estimated that annual production probably exceeds 10 million (Potter). They

Methods of Protecting Trees from Animals

- Fences and large cages are effective only if livestock and deer are the only animals of concern. Fences require a large initial investment and result in fenced areas being removed from livestock production. Fences and cages must be maintained regularly.
- Screen cylinders provide adequate short-term protection against insects, rodents, and deer but are ineffective against livestock and must be reopened once seedlings grow to the top, exposing plants.
- Seedling protection tubes are an inexpensive way to protect plants against rabbits and deer, but they are not effective against livestock, insects, or small rodents. Shoots that grow through the sides of tubes are vulnerable to browsing.
- Treeshelters have proven very effective in protecting rangeland oak seedlings from a wide range of animals and stimulating rapid, above-ground growth. They are relatively expensive but can greatly reduce the time required for seedlings to grow to sapling stage.
- Habitat modification can reduce damage from grasshoppers and some rodents, but it is ineffective for larger ranging animals, such as deer. Care must be taken to monitor the regrowth of vegetation or animals will quickly reoccupy site.

Recommended Procedures for Treeshelter Installation

- Select the size of treeshelter based on the browsing height of animals that are a threat.
- Install shelters so that they are upright and secure them to stakes using plastic ratchet clips or wire; make sure that seedlings are not damaged when shelters are secured to posts.
- Where treeshelters are used, plant in an aesthetic, "natural" arrangement rather than in regular, evenly spaced rows.
- Utilize stakes that are durable enough to last the length of time treeshelters will be in place and pound them at least 1 foot (31 cm) into the ground before planting seedlings.
- Make sure that the tops of stakes are lower than the tops of shelters to prevent access by rodents that can climb stakes and damage to seedling shoots from rubbing against stakes.
- To prevent seedling desiccation, install shelters with the base buried in the ground.
- To prevent bird access, install plastic netting over the tops of shelters.
- If treeshelters are placed in pastures grazed by livestock, secure the shelters to metal posts using wire and thread flexible wire through the top instead of using plastic netting.

are reported to not only protect seedlings from a variety of animals but also to stimulate above-ground growth. This growth stimulation seems to result from creating a mini-greenhouse inside the shelter, with elevated temperatures, humidity, and carbon dioxide concentrations. The higher relative humidity improves seedling moisture status by reducing transpiration. The treeshelters also help conserve moisture by condensing transpirational water on the tube interior. The condensation then drips back to the soil at the bottom of the shelter. Treeshelters can also make it easier to apply postemergent herbicides without risking contact of the chemical with the seedling's foliage (Potter 1988). Finally, treeshelters can help identify where seedlings are planted, which facilitates subsequent weed control and irrigation treatments; plants are also less likely to be accidentally mown or run over. As a result of these benefits, survival and growth in treeshelters is thought to be better. A large-scale survey of 193 sites in England that were planted with various tree species over the previous 12 years using treeshelters found that 89 percent of the shelters surveyed contained a living tree (Kerr 1995).

Although treeshelters have not been used for as long or as extensively in the United States, they have been evaluated in several oak field trials in California with promising results (Costello, Peters, and Giusti 1996; McCreary 1996; McCreary and Tecklin 1997; Tecklin, Connor, and McCreary 1997). They are effective in preventing animal damage from deer, rabbits, grasshoppers, and voles. When treeshelters are buried a few inches in the ground, they also seem to provide some protection against pocket gophers, though this has not been thoroughly evaluated. Finally, treeshelters show promise for use in pastures grazed by livestock (McCreary 1997; 1999) as long as they are secured to heavy-metal fence posts (fig. 27). But clearly they are not appropriate for all plantings, and, in many cases, it may be more cost-effective to utilize other protective measures.

Treeshelter Design, Construction, and Installation

There are several manufacturers of treeshelters and two main designs. The first design consists of flat sheets that can easily be shipped and transported. Once on site, they are rolled into cylinders or assembled into square boxes and placed over seedlings. The second major type of treeshelter design is made up of cylinders of extruded tubular plastic that need no assembly. The disadvantage of solid, cylindrical treeshelters is that they are bulky and expensive to ship and transport. Consequently, they are usually more expensive. Most types of treeshelters come in a range of heights.

Staking. Shelters more than 1 foot (31 cm) tall require attachment to a stake, usually with nylon ratchet clips, while some short types can be partially buried and are self-supporting. We have found that the nylon ratchet clips are easily broken when cattle rub against shelters and posts, and, therefore, recommend securing shelters to posts with wire in grazed pastures. It is important that the material securing the shelter to the stake not be wrapped directly around the seedling since this could obviously restrict growth and cause damage as seedlings become larger. After shelter installation, the supporting stakes should be several inches below the lip of the shelter to prevent contact with and damage to the emerging tree (fig. 28).

Stakes or posts can be made of a variety of materials, including wood, metal, and fiberglass. The stakes should be durable enough to last the length of time treeshelters are in place, be resistant to warping, offer frictional resistance to any twisting movement around

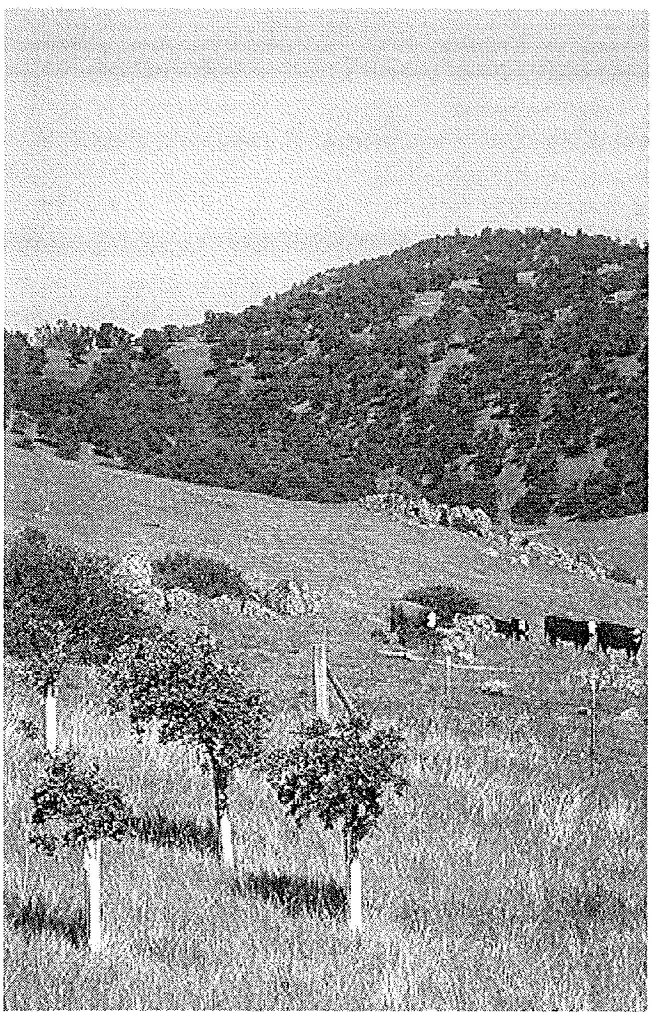

Figure 27. Treeshelters have been used effectively in establishing seedlings in areas grazed by cattle.

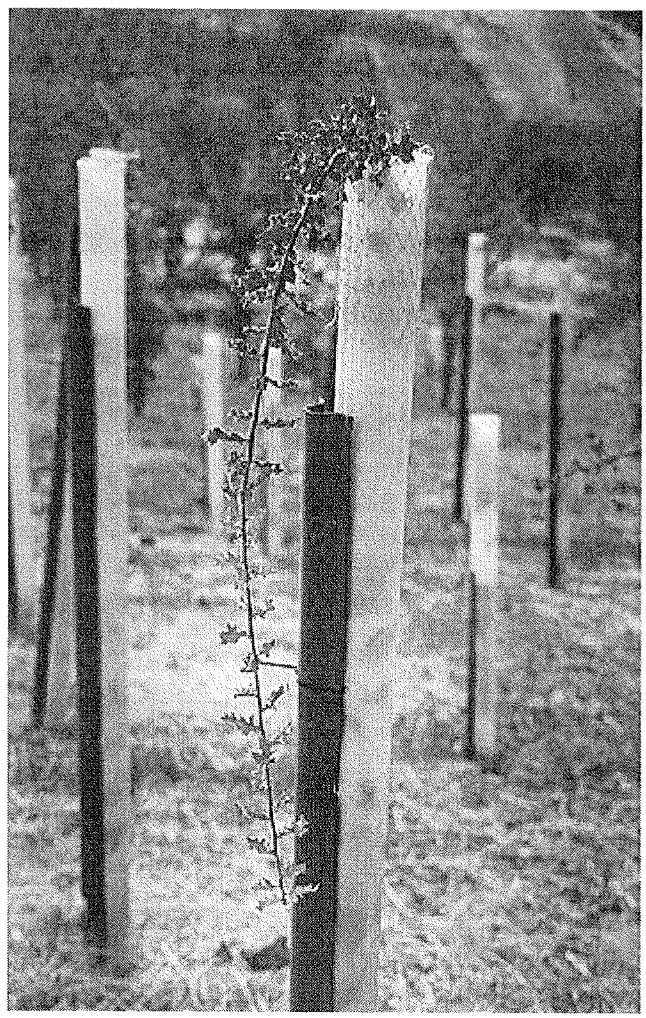

Figure 28. The supporting stakes on treeshelters should be several inches below the top of the tube itself.

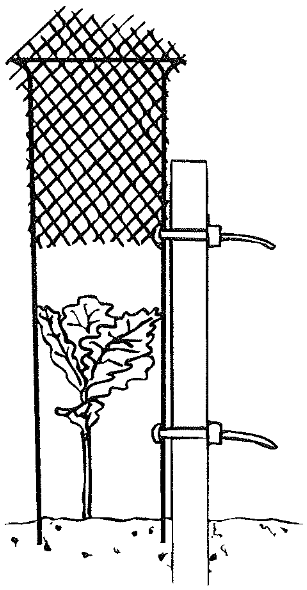

Figure 29. Treeshelters should be installed and maintained in an upright position.

Figure 30. This 13-foot giraffe tube was used to evaluate the effects of very tall treeshelters on oak seedling growth in England.

the stake, and be relatively easy to remove (Kerr 1996). We have found that oak stakes provided by manufacturers generally last 5 years, while 1-by-2-inch (2.5-by-5-cm) untreated, pine stakes can rot away below the ground after 1 or 2 years. We have also used 4-foot (1.2-m) pieces of rebar (steel-reinforcing rods) and standard metal fence posts. Both are durable and last far longer than necessary, but they generally require a post-pulling tool to take them out of the ground when the shelters are removed. It has been suggested that seedling root may grow around the metal flange at the bottom of the fence posts, causing injury to the seedling when the post is removed, but this has not yet been evaluated.

Advantages of Solid-Construction Treeshelters. While solid-construction treeshelters are generally more expensive, they have several advantages over types that require assembly. First, once on site they are relatively easy to place over planting spots. Second, they are inherently more sturdy and, consequently, can more easily be sunk into the ground around the seedlings. This can be important since a gap between the shelter base and the ground can create a "chimney effect," resulting in more desiccating conditions inside the shelter. In the Mediterranean climate of California where moisture stress often limits establishment success, such desiccation can be lethal. Solid shelters are also less likely to be dislodged or damaged by buffeting winds or animals that rub against them. Finally, solid-design treeshelters generally require less maintenance after they are installed, less frequent return visits to make sure they remain attached to the stake, do not have weeds growing inside them, and function properly. For woodland plantings in England, Vickers (1999) estimated that the average cost of maintaining solid-construction treeshelters to original specifications for a planting density of 450 per acre (1,112/ha) would vary between $50 and $150 per acre ($124 and $372/ha).

Colors. In addition to different shapes and sizes, treeshelters also come in several colors, including beige, orange, white, and clear. Beige shelters, which are designed to blend in with surrounding vegetation, are reported to reduce light intensity by approximately 50 percent, while white shelters reduce it by approximately 30 percent (Kjelgren, Montague, and Rupp 1997). In low light situations, such as plantings under canopies, white or clear shelters may, therefore, be preferable. From an aesthetic point of view, white shelters can be unsightly, especially if seedlings are planted in evenly spaced rows, which can give the planting area the appearance of a cemetery. In general, it is recommended that beige shelters be used in open-area plantings, with seedlings planted in irregular patterns, rather than in a systematic grid. Care should be taken to install and maintain shelters in an upright position and to check them and remove weeds that may be growing inside (fig. 29).

Heights. Treeshelters come in a variety of heights, ranging from 8 inches to 6 feet (20.5 cm to 1.8 m). Some trials in England have even used treeshelters that are 13 feet (4 m) tall (Windell 1993) (fig. 30). Not surprisingly, taller shelters are more expensive. Therefore, it is generally advisable to use shelters that are only as tall as necessary to protect against animals that are a threat. For example, if voles are the only concern, shelters that are 1 foot (31 cm) in height should be adequate. For rabbits, shelters that are 2 feet (.6 m) tall can be used. We have found that for deer and cattle at the University of California Sierra Foothill Research and Extension Center, 4-foot (1.2-m) shelters are tall enough. However, both deer and cattle can clearly reach up and nip seedlings emerging from the tops of 4-foot (1.2-m) shelters, so if browsing pressures are intense (resident deer or confined livestock), it may be necessary to use shelters that are 5 or even 6 feet (1.5 or 1.8 m) tall. It is also important to keep in mind that the effective height of a treeshelter is reduced when used on steep or uneven terrain since browsing animals can stand upslope and more easily reach seedlings. While treeshelters are relatively expensive compared to some other seedling protectors, the cost in the United States has dropped considerably in the last several years. Currently a 4-foot (1.2-m), solid-construction treeshelter, without the stake, costs approximately $3.

In 1995, a treeshelter conference in Pennsylvania surveyed the current state of knowledge on treeshelters used in reforestation and ecological restoration. The proceedings were published by the U. S. Forest Service (Brissette 1996) and are a good reference. Other references include a comprehensive booklet describing the use of treeshelters in Great Britain (Potter 1991) and a general description of the use of treeshelters in the United States and elsewhere (Windell 1992). A large U. S. Forest Service research project has also compared the effectiveness of various treeshelter designs and commercial products (Windell and Haywood 1996).

Trapped Birds. A potential problem associated with treeshelters is that birds can become trapped inside. Western blue birds (*Sialia mexicana)* have been identified as one species prone to this. To reduce the possibility of this happening, some manufacturers provide plastic netting to place over the tops of shelters, creating a physical barrier (albeit fairly flimsy) to entry. Advertisements also state that these nettings prevent the entry of butterflies that can also become trapped. We recommend using these net protectors and have observed them to work reasonably well, as long as they remain in place and are not blown off.

However, where livestock are present, netting is generally not effective. Cattle invariably take the netting in their mouths, chew it up and spit it out. Where cattle are present, we recommend replacing netting with flexible wire threaded through the top of the treeshelter as described by Tecklin (1993) (fig. 31). The wire should be removed as the tree grows up and out of the shelter.

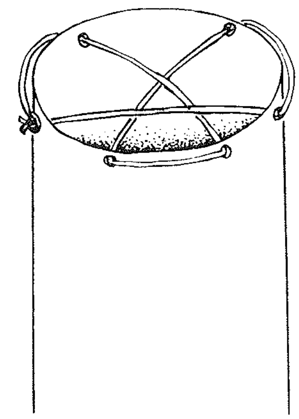

Figure 31. Flexible wire threaded through the top of a treeshelter can be substituted for netting to prevent bird entry when cattle are present.

Oak Seedling Growth in Treeshelters

In addition to providing effective protection against a wide range of animals, treeshelters have also increased the growth of blue and valley oak seedlings in trials at the University of California Sierra Foothill Research and Extension Center and elsewhere (McCreary 1997; McCreary and Tecklin 1993a, 1993c; McCreary and Tecklin 1996). On average, height growth in the first 2 years tripled compared with growth of unsheltered seedlings in plots where animal damage was not a consideration (fenced and weeded). Costello, Peters, and Giusti (1996) also reported better growth for blue oak, valley oak, and coast live oak protected with treeshelters, but these differences were greatest in irrigated, rather than unirrigated plots. In two separate trials (Burger, Forister, and Kiehl 1996; Burger, Forister, and Gross 1997), it was reported that valley and coast live oak seedlings in

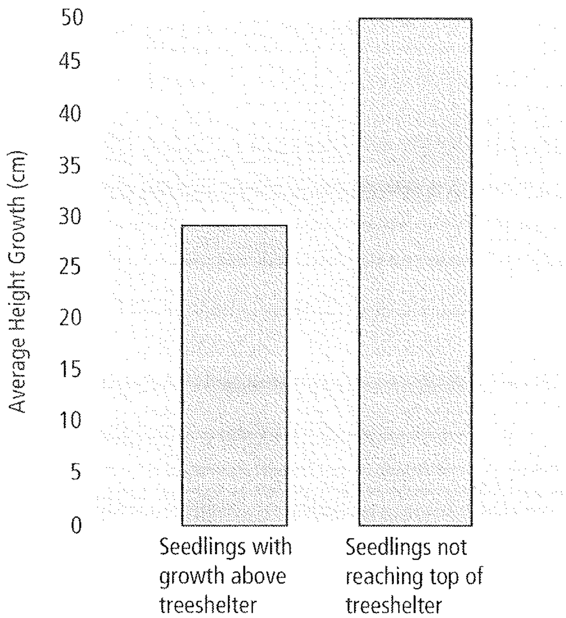

Figure 32. Annual height growth changes once a seedling grows above the top of the treeshelter.

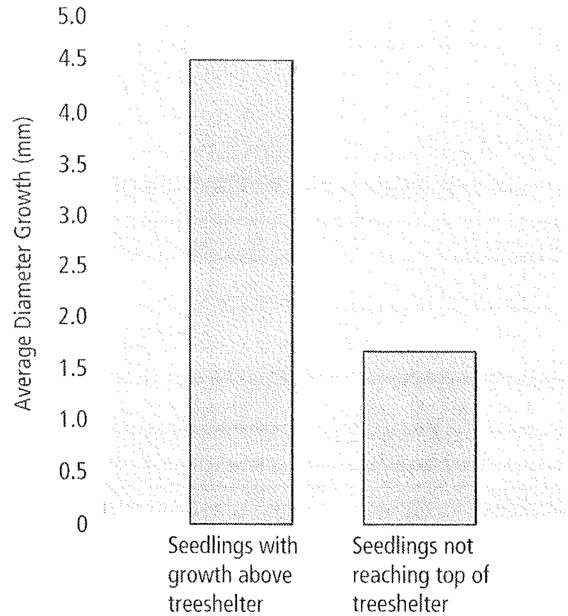

Figure 33. Annual diameter growth changes once the seedling grows above the top of the treeshelter.

treeshelters were taller compared to unsheltered seedlings during the first year of growth. After 2 years, however, they were not significantly taller.

Diameter Growth. Treeshelters do not seem to lead to an increase in the diameter growth of seedlings. In trials at the SFREC, most blue oak seedlings in treeshelters grew taller but had diameters similar to controls, resulting in seedlings inside shelters that were tall and thin. To evaluate this further, we established a trial to examine different shelter heights (2, 4, and 6 feet [.6, 1.2, and 1.8 m]). We measured the annual height and diameter growth while seedlings were still inside shelters, as well as after they had grown up and out of the tops (McCreary and Tecklin 2001). Height growth was consistently greater while seedlings were shorter than the shelters, regardless of shelter size (fig. 32). As soon as seedlings grew above the tops of the shelters, however, height growth diminished and diameter growth increased (fig. 33). As a consequence, when seedlings were below the tops of the tubes, they were tall and spindly. If the shelters had been removed at this point, the plants would almost certainly have toppled over without staking. After several years of growth above shelters, their girth increased greatly (while height growth slowed markedly), and they were larger, more robust plants than their unsheltered counterparts.

Costello, Peters, and Giusti (1996) found that when shelters were removed from three species of California oaks after 4 years, most saplings had sufficiently well-developed trunks to maintain an upright position (fig. 34). We recommend that shelters not be removed for at least 3 years after the seedlings have emerged from the tops. Treeshelters can be left in place longer, but should be removed before they restrict diameter growth (see **Treeshelter Durability and Maintenance**, below).

Burger, Forister, and Kiehl (1996), working with 10 species of landscape trees, including valley oak and coast live oak, recommended removing treeshelters as soon as young plants emerge from the tops and then staking them. They found that the benefits of shelters, in terms of accelerated growth, decreased with time. This research, however, focused on ornamental trees where greater costs of establishment—including staking—may be more easily justified. In almost all wildland planting situations, protecting oak seedlings from animals for at least 3 to 5 years is critical for success, and shelter removal before that time could result in unacceptable damage.

Effects on Roots. There is an additional concern that even though the use of treeshelters increases growth, this aboveground growth may be at the expense of the roots, resulting in plants that have a poor root to shoot

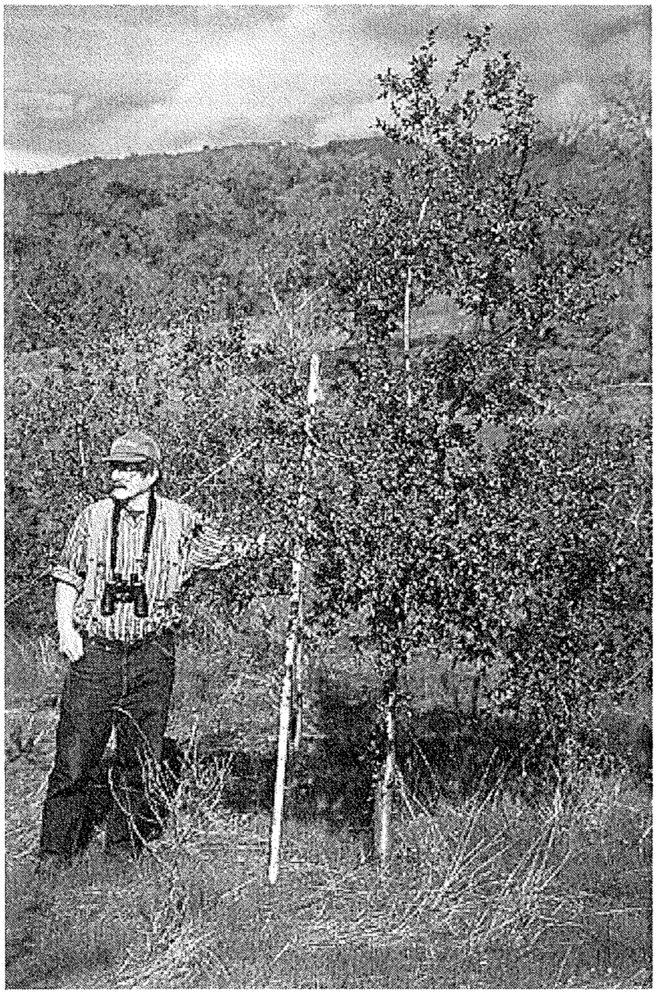

Figure 34. These seedlings were in treeshelters for 4 years. They continue to stand upright after the treeshelters are removed.

ratio. Rendle (1985) reported that treeshelters altered the distribution of dry matter in English oak, causing seedlings to have larger shoot to root ratios. Burger, Svihra, and Harris (1992) also found that oaks grown in containers had growth ratios for aboveground and belowground growth that were out of balance. Burger, Forister, and Gross (1997) further reported that after 2 years in a nursery setting, treeshelters reduced root dry mass, root to shoot ratios, total root length, and total root mass for valley oak, as well as the aboveground biomass for valley oak and coast live oak. However, these studies were of short duration, and these ratios may again change as plants grow older. Ponder (1996), for instance, found that sheltered, northern red oak seedlings, harvested 3 years after outplanting in forest openings, had both higher stem and root weights than seedlings not protected with shelters.

Treeshelters have also been effectively used to "retrofit" both natural and planted oak seedlings that are stunted (Gillespie, Rathfon, and Meyers 1996; Tecklin, Connor, and McCreary 1997; Shuler and Miller 1996). This has resulted in greatly accelerated growth. In the Tecklin trial at the SFREC, unprotected blue oak seedlings that had languished in an experiment for 2 years and averaged only 6 inches (15 cm) in height, suddenly grew vigorously when treeshelters were placed over them. After being protected for 2 years, they averaged more than 3 feet (.9 m) in height, while unprotected seedlings continued to grow slowly and averaged less than 1 foot (31 cm) tall.

Treeshelters with California Black Oak. We have also used treeshelters with California black oak, but with very different results. In a trial with this species, treeshelters did not promote accelerated height growth, and seedlings in all treatments, including uncovered controls and seedlings covered with seedling protection tubes, remained quite small, even after 3 years. Friske (1997) used treeshelters with California black oak in Yosemite National Park and, after 6 years, found that while seedlings in treeshelters were significantly taller than those in open plastic mesh, they averaged less than 2 feet (.6 m) in height. It is unclear why this oak species seems to initially grow so slowly, both with and without treeshelters.

Treeshelter Durability and Maintenance

Most shelters do not deteriorate readily. They remain intact for a number of years (for durability comparisons, see Windell and Hayward 1996) because they have stabilizing ultraviolet inhibitors added to the plastic. In early trials without stabilizers, treeshelters broke down before seedlings had grown large enough to be self-supporting. While attempts have been made to incorporate a quantity of inhibitors that will result in timely degradation (3 to 5 years), this has not been routinely successful and the treeshelters have not degraded as expected (Kerr 1992). Strobl and Wagner (1996) could detect no photodegradation of treeshelters after 5

Recommended Treeshelter Maintenance Procedures

- Visit shelters at least once each year to make sure they are upright, attached to the stake, buried in the ground, and functioning properly.
- Keep a 4-foot (1.2-m) diameter or larger circle around shelters free of weeds for at least 2 years after planting, and remove weeds that grow inside shelters.
- Replace flexible netting that has blown off shelter tops.
- Replace stakes that have rotted or broken.
- Leave shelters in place for at least 3 years after seedlings have grown out the tops, longer if shelters are still intact and are effectively protecting seedlings.
- Remove shelters if they are restricting growth or abrading seedlings; to remove solid shelters, slice down the sides with a razor or knife, being careful not to damage the seedling inside.

years. This raises the question of when treeshelters should be removed. In England, Kerr (1996) recommends removing shelters before they begin restricting the diameter growth of the saplings, or when treeshelters are abrading and severely damaging trees. Until this point, treeshelters help provide support and prevent damage from rabbits, squirrels (which are a terrible pest in England and can girdle trees by stripping bark), and deer (browsing and antler rubbing). For most California species, however, growing to this size could take a decade or more, and there may be aesthetic or environmental reasons to remove shelters earlier. However, it is important to leave shelters in place for at least 3 years after seedlings have emerged from the top.

By the time seedlings are taller than the tops of shelters, it is usually impossible to slip the solid shelters over the seedlings, but it is fairly easy to slice these shelters down the side using a razor or utility knife so they can easily be removed. It is especially important that treeshelters be split or removed before trees become so large that their diameters are as great as that of the shelters. At this point, stem deformation or even sapling death can occur. To reduce this possibility, some treeshelter manufacturers have begun incorporating a strip down the sides with a preformed weakness in the plastic. This is intended to permit the shelters to split apart when plants grow and press against the sides of the shelters. Whether or not this will work reliably is yet to be determined.

Finally, even though treeshelters have been shown to improve water relations and accelerate seedling growth, it is important to caution that they do not eliminate the need for weed control. Kerr (1996) noted that "the use of effective weed control in combination with treeshelters is very important to ensure rapid establishment of young trees." It is also important to remove weeds growing inside shelters because the favorable environment inside can lead to rapid weed growth.

Fertilization

There have been relatively few fertilization trials with native California oak plantings, and those that have been conducted have had mixed results. Adams, et al. (1987) reported a negative effect of granular, slow-release fertilizer (18-6-12) placed beneath blue and valley oak acorns and transplants at time of planting. Tappeiner and McDonald (1980), however, reported that annual fertilization with ¼ pound (113 g) per seedling of 16-20-0 enhanced survival and height growth of California black oak. McCreary (1996) also found that .74-ounce (21-gm), slow-release, fertilizer tablets (20-10-5), placed below outplanted blue oak acorns and seedlings, significantly increased both diameter and height growth. In the eastern and northern United States, fertilizers have been consistently reported to improve oak seedling performance (Johnson 1980). Differences in the California findings may be partially explained by an interaction with weed growth. In the first trial mentioned (Adams et al. 1987), weeds were not completely controlled and may have benefited more from the fertilizer than the seedlings, resulting in greater competition. In other trials, the plots were kept largely weed-free, and increased competition was not a problem. Obviously, soils can also vary tremendously in their fertility, and seedling response to fertilizers varies accordingly.

Compared with other costs associated with artificial regeneration, fertilization is inexpensive. The .74-ounce (21-gm) tablets used in the study above (McCreary 1996) cost about 5¢ each in 1993 when purchased in bulk, so even small improvements in performance were worth the costs. Since they are so inexpensive, we recommend using fertilizer tablets, placing them 3 to 4 inches (7.5 to 10 cm) below seedling roots at the time of planting.

Irrigation of Rangeland Oaks

When, Where, and How Much to Irrigate

In large-scale, wildland plantings, irrigation is generally not practical, especially if there is not an available water source near the planting area. In some settings, however, especially where cost is not as great a concern, it may be possible to water seedlings for several years after planting. Because water stress can seriously limit seedling survival and growth, irrigation can greatly improve the chances of establishment, especially on dry sites.

Effects of Different Soils. Sites and soils are very different and can have a tremendous effect on moisture-holding capacity and the availability of water for the seedlings. Plantings in deep, sandy, alluvial soils along the Sacramento River may need to be watered almost daily during the first year after planting. In the heavier, shallower soils at the University of California Sierra Foothill Research and Extension Center, however, this is not the case. We conducted a trial with newly planted valley oak seedlings at the SFREC that compared four treatments: no irrigation, 1 gallon (3.8 L) of water weekly, 1 gallon (3.8 L) every 2 weeks, and 1 gallon (3.8 L) every 4 weeks (McCreary 1990b). All 30 seedlings from each treatment in this study survived, indicating that irrigation was not necessary for establishment. After the first year, those that received any of the three irrigation treatments were significantly taller than unirrigated plants, but there were no significant differences among the three irrigated groups. This suggests that 1 gallon (3.8 L) of water every 4 weeks was sufficient during the first year in these soils and this environment.

In a study that evaluated soil moisture availability as a factor affecting valley oak establishment at The Nature Conservancy's Cosumnes River Preserve, irrigated, field-planted seedlings grew vigorously while unirrigated seedlings had greater water stress, less growth, and higher mortality (Meyer 1991). Bernhardt and Swiecki (1991) examined the value of irrigating direct-seeded valley oak and found that irrigation initially had a significant positive effect on seedling growth at two of three sites. However, irrigation was extremely expensive compared with moisture-conserving mulching treatments. Six years after planting, irrigation showed no positive effects on survival or growth, and it was observed that "irrigated seedlings generally sustained greater damage from small herbivores than did unirrigated seedlings. Damaging animals may be attracted to irrigated sites by the moist soil or increased succulence of oak tissues" (Bernhardt and Swiecki 1997).

Fertilization, Irrigation, and Top Pruning

- Place .74-ounce (21-g), slow-release fertilizer tablets (20-10-5) 3 to 4 inches (7.5 to 10 cm) below planted acorns or seedlings.
- Irrigation in many situations is not necessary if there is timely and thorough weed control.
- If irrigation is needed for establishment and the terrain is steep or percolation of water through soil is slow, construct earthen irrigation basins.
- Provide irrigation in the form of infrequent, deep irrigations rather than frequent, shallow irrigations; time irrigations to extend the rainy season.
- Always control competing vegetation, even in situations where supplemental irrigation is provided.
- Top-prune seedlings at the time of planting if they are too tall and are out of balance with root systems; prune small, liner stock back to a 6-inch (15-cm) top.

Irrigation Varies by Species. Light and Buchner (1999) found that optimum irrigation amounts varied for four oak species evaluated on California's North Coast. Providing water enhanced growth of each species, but there were levels of irrigation above which growth declined. Oregon white oak, for instance, performed best on a frequent irrigation schedule that caused blue oak growth to decline. At lower levels of irrigation, however, blue oak growth peaked, while the performance of Oregon white oak declined. They concluded that to thrive, all of the oak species evaluated (which also included California black oak and interior live oak) needed "appreciably more water than is available from rainfall alone."

Effects of Weed Control. It is important to remember that the need for irrigation is closely related to weed control. In almost all situations where there is little or no weed control, irrigated seedlings will still be under moisture stress. In fact, supplemental water can cause so much growth of competing plants that oak seedlings are adversely affected. Eliminating competing vegetation can lessen water stress and greatly reduce or even do away with the need for supplemental water. At the SFREC,

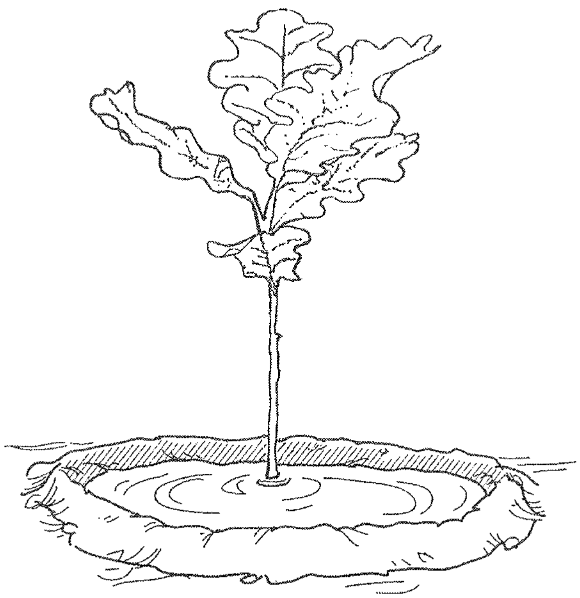

Figure 35. An earthen water basin can prevent rapid runoff of irrigation water.

which averages 28 inches (71 cm) of rainfall annually, we have concluded that supplemental irrigation is not necessary in our blue, valley, and interior live oak trials as long as we maintain areas around seedlings free of weeds for at least 2 years (preferably longer). Planting seedlings late in the season when soils are already becoming dry creates an exception. In this situation, we like to water-in seedlings to make sure that there is adequate initial moisture in the soil and air pockets are eliminated.

Earthen Basins. In many oak plantings that are irrigated, earthen basins are constructed around individual seedlings to form a reservoir that can hold several gallons of water (Bush and Thompson 1989). This is especially important in heavier soils where percolation can be slow and on slopes where irrigation water would run off too rapidly. With a basin, a large quantity of water can be added and then left to soak in gradually. Generally, these basins are 1 to 2 feet (30 to 61 cm) wide, with sides that are several inches tall (fig. 35). They need to be reasonably level, however, or water will drain out of them when they are filled. Basins have an added advantage of capturing greater quantities of rainfall, so even without irrigation, the soil moisture conditions in the rooting zone should be improved. Basins can be difficult and time consuming to construct, especially in hard, compacted, or rocky soil. This adds to the cost of planting and must be considered along with the benefits expected. In drier regions, and especially where plants will be irrigated occasionally, basin construction is probably a good investment. We generally do not use them at the SFREC since we have found that irrigation is not necessary, as long there is good weed control. At a planting in Walnut Creek, however, basins were essential because plantings were on steep slopes. Without basins, irrigation at this site would have been ineffective.

Potential Risks of Disease with Summer Irrigation

It is well recognized that summer irrigation around native California oaks can prove deadly, since diseases such as oak root fungus (*Armillaria mellea*) and crown rot (*Phytophthora cinnamomi*) proliferate where it is warm and wet, conditions which normally do not occur in the Mediterranean climate of the state (Raabe 1980). Irrigation around mature oak trees, which have evolved in conditions where summer rainfall is rare, should be avoided. Consult any arborist and you will hear horror stories of magnificent oak trees lost to disease after a homeowner put in a lawn beneath them and began watering. But, while there has not been much research on the summer irrigation of oak seedlings, it appears that small seedlings are less sensitive to diseases from warm and moist soils. Also, the benefits of summer irrigation can outweigh the risks for seedlings that are under substantial moisture stress. To reduce potential risks from watering, it is recommended that irrigation be deep and infrequent rather than often and shallow. If only several waterings are planned, it is better to time them to extend the normal rainy season into late spring rather than provide water in the middle of summer.

Superabsorbants

There are a variety of soil amendments on the market that claim to reduce moisture stress on plants. Many of these are superabsorbant hydrogels, polymers that absorb and retain several hundred times their own weight in water. Theoretically, they improve water relations by binding water when it is available and then slowly releasing it. These materials do not create any new water, but they can influence moisture availability over time. While the effectiveness of these materials is debated, it is hard to imagine a situation where they would be particularly useful for wildland oak plantings. First and foremost, it would be prohibitively expensive to mix these materials into the soil where the oaks are to be planted. A variation of these materials are containers similar to milk cartons that contain a polymer gel. These are placed in the ground next to planted seedlings. The material inside the 1-pint (.47-L) or 1-quart (.95-L) container is supposed to slowly release moisture to the target plant over a period of several months. We did a small field trial evaluating blue oaks with and without these containers and could find no benefit.

Shading Oak Seedlings

Blue oak has been characterized as highly intolerant of shade (Sudworth 1908), and it has been reported that blue oak saplings do not survive under dense shade (Swiecki and Bernhardt 1998). However, there is some evidence that providing artificial shade may improve field performance of planted blue oak in certain situations. Muick (1991) compared the response of directly-sown blue oak acorns in full sunlight and 50 percent shade and found that shade improved both emergence and survival. Artificial shade provided by placing commercially available "shadecards" on the south side of seedlings has been reported to improve Douglas fir survival in some situations (Helgerson 1990), and shade may offer some benefit for oaks on dry exposed sites, although the gains are likely to be small. We used black plastic shadecards in one study with blue oaks at the University of California Sierra Foothill Research and Extension Center but found that seedlings quickly grew above them. We could detect no improvement in survival or growth (McCreary 1989) from this treatment and have not used shadecards since.

Top Pruning Oak Seedlings

Studies outside of California have indicated that there are benefits from top pruning oak seedlings, both before and after lifting from bareroot nurseries (South 1996; Johnson 1984) or just after outplanting (Adams 1984). This is done to create plants of uniform size with more favorable shoot to root ratios. In California there has been no research on top pruning oaks in nurseries. At SFREC, we did a trial to test whether top pruning after field planting would be beneficial (McCreary and Tecklin 1993b). One-year-old blue oak seedlings in containers were top pruned at the time of field planting and compared with both large and small, unpruned controls. After two growing seasons, top pruned seedlings had significantly greater height and caliper increments than the other seedling types, suggesting that seedlings with large tops should be top pruned before or just after field planting to enhance performance.

Appendix A

Nurseries That Sell Oak Seedlings and Saplings

Below is a list of some of the wholesale and retail nurseries in California that produce native oaks in various sizes, ranging from seedlings in liners to specimen trees. The species of oaks grown at each nursery are not identified since this depends on several factors, such as acorn availability and demand, and can vary from year to year. Please contact the nursery for a current list of species and stock sizes available.

All Seasons Nursery
McKnew Enterprises
P. O. Box 2128
Elk Grove, CA 95759
916-689-0902
http://www.growtube.com

Arrowhead Growers
990 Rutherford Cross Road
P. O. Box 398
Rutherford, CA 94573
707-963-5800

Bitterroot Restoration Inc.
55 Sierra College Boulevard
Lincoln, CA 95648
916-434-9695

Blue Oak Nursery
2731 Mountain Oak Lane
Rescue, CA 95672
530-677-2111

Calaveras Nursery
1622 Highway 12
Valley Springs, CA 95252
209-772-1823

California Conservation Corps
Napa Satellite Center
P. O. Box 7199
Napa, CA 94558
707-253-7783

California Department of Forestry and Fire Protection
L. A. Moran Reforestation Center
P. O. Box 1590
Davis, CA 95617
530-753-2441

California Flora Nursery
2990 Somers Street
P. O. Box 3
Fulton, CA 95439
707-528-8813

Circuit Rider Productions, Inc.
Native Plant Nursery
9619 Old Redwood Highway
Windsor, CA 95492
707-838-6641

Cornflower Farms
P. O. Box 896
Elk Grove, CA 95759
916-689-1015

Drought Resistant Nursery
850 Park Avenue
Monterey, CA 93940
831-375-2120

Elkhorn Native Plant Nursery
P. O. Box 270
Moss Landing, CA 95039
831-763-1207

Freshwater Farms
5851 Myrtle Avenue
Eureka, CA 95503
800-200-8969

J. M. Oak Tree Nursery
430 La Lata Place
Buellton, CA 93427
805-688-5563 *(by appointment only)*

King Island Wholesale Nursery
8458 West Eight Mile Road
Stockton, CA 95219
209-957-6212

Las Pilitas Nursery
3232 Las Pilitas Road
Santa Margarita, CA 93453
805-438-5992
http://www.laspilitas.com

Matsuda Nursery
8501 Jackson Road
Sacramento, CA 95826
916-381-1625

Native Oak Nursery
45 Webb Road
Watsonville, CA 95076
831-728-8662

Native Revival Nursery
8022 Soquel Drive
Aptos, CA 95003
831-684-1811

Native Sons Wholesale Nursery
379 West El Campo Road
Arroyo Grande, CA 93420
805-481-5996

North Coast Native Nursery
P. O. Box 744
Petaluma, CA 94953
707-769-1213

Specialty Oaks Inc.
12552 Highway 29
Lower Lake, CA 95457
707-995-2275
http://www.specialtyoaks.com

Tree of Life Wholesale Nursery
P. O. Box 736
San Juan Capistrano, CA 92693
949-728-0685

Village Nurseries
1589 North Main Street
Orange, CA 92867
800-542-0209

Yerba Buena Nursery
19500 Skyline Boulevard
Woodside, CA 94062
650-851-1668

Appendix B

Sources of Materials for Oak Regeneration Projects

TREESHELTERS AND SEEDLING PROTECTION TUBES

All Seasons Nursery
McKnew Enterprises
P. O. Box 2128
Elk Grove, CA 95759
916-689-0902
http://www.growtube.com

Treegard—Albert F. Kubiske
3825 Highridge Road
Madison, WI 53704
608-837-9093

Terra Tech
International Reforestation Suppliers
2635 West 7th Place
Eugene, OR 97402
800-321-1037
503-345-0597

American Forestry Technology, Inc.
100 North 500 West
West Lafayette, IN 47906
765-583-3311

Tree Pro
3180 West 250 North
West Lafayette, IN 47906
800-875-8071
http://www.treepro.com

Tree Sentry Treeshelters
P. O. Box 607
Perrysburg, OH 43552
419-874-6950

Treessentials Company
2371 Waters Drive
Mendota Heights, MN 55120-1163
800-248-8239

ROOT GUARD

Digger's Product Development, Inc.
P. O. Box 1551
Soquel, CA 95073-2531
831-462-6095

CONTAINERS

Stuewe & Sons, Inc.
2290 Southeast Kiger Island Drive
Corvallis, OR 97333
800-553-5331
http://www.stuewe.com

Monarch Manufacturing
13154 County Road 140
Salida, CO 81201
800-284-0390
http://www.monarchmfg.com

Spencer-Lemaire Industries Limited
11406—119th Street
Edmonton, Alberta
Canada T5G 2X6
800-668-8530

SHADECARDS

Terra Tech
International Reforestation Suppliers
2635 West 7th Place
Eugene, OR 97402
800-321-1037
503-345-0597

MULCH MATS

Treessentials Company
2371 Waters Drive
Mendota Heights, MN 55120-1163
800-248-8239

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An Evaluation of Coast Live Oak Regeneration Techniques[1]

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Abstract: *A test to evaluate four planting techniques for coast live oak (*Quercus agrifolia *Née) was established in spring 1992 on the California Polytechnic State University, San Luis Obispo, California. Treatments included tree shelters (Tubex®), oak leaf mulch, tree shelters plus mulch, and an unprotected control. Seedling survival 1 year after planting ranged from 14.3 to 37.1 percent. The greatest survival was obtained with oak mulch, and the tallest seedlings, but lowest survival, with tree shelters. Although the shelters enhanced seedling growth, the seedlings averaged only 5.9 inches in height at 1 year. Because of poor survival, empty planting spots were replanted in 1993, 1994, and 1995. By December 1995, average coast live oak stocking ranged from 60 to 74 percent, and height from 3.5 to 15.6 inches for the control and tree shelter treatments, respectively.*

This report describes a project in which several techniques were used to enhance the survival of direct seeded coast live oak (*Quercus agrifolia* Née). What was initially intended to be a 1-year planting project evolved into a 4-year planting "marathon." This is the only effort in California that we are aware of in which the same plantings spots were seeded 4 successive years to achieve as close to 100 percent stocking as possible. Surveys during the past several years indicate a general lack of adequate coast live oak regeneration throughout its range. Bolsinger (1988) reported that about 90 percent of the coast live oak type had few or no saplings or seedlings. And, attempts to artificially regenerate coast live oak in local wild environments have not been successful (Muick 1991, Plumb and Hannah 1991).

A myriad of causes have been identified to explain the poor success of both natural and artificial restocking (Davis and others 1991, Swiecki and others 1990). Swiecki and Bernhardt (1991) provide an excellent overview of the factors affecting the restoration of valley oak (*Q. lobata* Née). Most of these factors apply to coast live oak as well. Herbivory and moisture stress are two key factors negatively affecting both seedling establishment and survival. Mice (Davis and others 1991), deer (Griffin 1971), cattle (McClaran 1987), and grasshoppers (McCreary and Tecklin 1994) are some of the biota that can cause significant seedling losses. However, once established, oak seedlings can often survive stem and foliage losses because of their resprouting capacity. On the other hand, gophers can kill both seedlings and saplings, and they can destroy a root system, preventing resprouting (Adams and others 1992, Davis and others 1991, Lathrop and Yeung 1991). Where gophers are present, the root systems must be protected.

A wide variety of protective devices have been used to prevent herbivory, including window screens (Adams and others 1992, McCreary and Tecklin 1994), fencing (Davis and others 1991, Tietje and others 1991), and individual plant exclosures (Plumb and Hannah 1991, Swiecki and Bernhardt 1991). Plastic translucent tubes called tree shelters (Tubex®) have received considerable attention during the past few years (Costello and others 1991, Potter 1988). They are touted not only because they protect seedlings from herbivory, but also because they promote height growth (McCreary 1993).

[1]An abbreviated version of this paper was presented at the Symposium on Oak Woodlands: Ecology, Management, and Urban Interface Issues, March 19-22, 1996, San Luis Obispo, Calif.

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Moisture stress is a major environmental factor responsible for poor germination (Plumb and Hannah 1991) and seedling death (Barnhart and others 1991, Lathrop and Yeung 1991). Low rainfall, an obvious contributor to moisture stress, was considered the major reason for poor success of regeneration work during the latter part of the 1980's (Plumb and Hannah 1991). Other major causes of water stress are plant competition, particularly from annual grasses (Adams and others 1992, Davis and others 1991), and coarse soil textures (Plumb and Hannah 1991). Competing vegetation can be controlled with herbicides and mulching (Adams and others 1992, McCreary 1991). Irrigating young plants during the dry season has also been used in several oak regeneration studies (Costello and others 1991, Swiecki and Bernhardt 1991). The latter obtained better height growth with irrigation.

Some of the many factors that affect oak seedling germination and survival have been briefly noted. The main objective of the work reported here was to determine the effect of tree shelters, oak leaf mulch, and summer irrigation on coast live oak seedling survival. Because of low seedling survival, we decided to replant the same planting spots to determine how much additional work would be needed to achieve a high level of stocking.

Methods

Site Description

The study area is located on Radio Tower Hill (RTH), just west of the main California Polytechnic State University (Cal Poly) campus, San Luis Obispo, California. It is on a northeast aspect at about 400 feet in elevation with slopes between 10 to 40 percent. The test plots occupy about 0.5 acres in a long narrow strip between a ridge line and a stand of coast live oak along the northeast border. A preliminary analysis indicated that the soil is a loamy, mixed, thermic, ultric soil that was keyed out to be a Catelli coarse, sandy clay loam. Except for thicker "O" and "A" horizons, there is little difference between the soil in the grassy plot area and that under the adjacent oak canopy (*table 1*).

***Table 1**—Comparison of soil characteristics between the open grassy test area and under the canopy of the adjacent oak stand*

		Soil horizon depth					Accumulated
Site	pH	O[1]	A	B	BC	C	depth to "A" to "C"
		inches					
Open grass	5.4-5.7	0.4	1.6	8.3	5.1	13.8+	15.0
Oak canopy	5.5-5.8	0.8	4.7	8.7	3.9	9.9+	16.3

[1]Soil horizons are defined as follows: O = organic zone, A = mineral zone, B = accumulation zone, and C = unconsolidated parent material.

Annual grasses are the predominant vegetation on the project area with scattered northern monkey flower (*Mimulus aurantiacus* Curtis), coyote bush (*Baccharis pilularis* DC.), and California sage brush (*Artemisia californica* Less). There is also scattered advanced coast live oak regeneration in the annual grass along the upper edge of the oak stand, including several new seedlings along the canopy drip line. The oak stand is composed of a wide range of sizes and conditions of coast live oak. Photographic evidence over the past 82 years indicates that there has been a considerable increase in the size of the stand since 1908.

Although no formal animal monitoring was done, deer (*Odocoileus hemionus columbianus*) are often seen in the plot area. There was evidence of extensive pocket gopher (*Thomomys bottae* Eydoux & Gervais) activity at the beginning of the study that seemed to greatly increase in 1995. In some areas, exit and feeding holes are only 6 to 12 inches apart. Grasshoppers (species not identified) were present throughout the summer months; but in summer 1994, as noted by McCeary and Tecklin (1994) at the Sierra Field Station, there was a population explosion. It was common to find four or five grasshoppers on a single seedling. Leaf and stem damage was similar to that described by McCreary and Tecklin (1994)—leaves partially to completely gone and bark stripped from the smaller stems.

Treatments

This project included a small statistically designed regeneration test to compare the effectiveness of tree shelters and oak leaf mulch on coast live oak seedling survival and growth. Because of poor initial seedling survival, planting spots without a live seedling were replanted for 3 additional years. A small irrigation study was also established the third year of the project.

1991-1992 Activities

The Regeneration Test involved four treatments: (1) untreated control, (2) oak litter mulch, (3) tree shelters (4 feet tall and 3.5 inches wide), and (4) tree shelters plus oak litter mulch. The test consisted of 35 randomly located clusters, each containing four planting spots randomly assigned to the treatments. The planting spots in each cluster were in a square pattern and about 4 feet apart. Planting data, site preparation, seed source, and irrigation schedule are listed in *table 2*. All planting spots were pre-dug with a 6-inch power auger to a depth of 12 to 18 inches. An 18-inch long by 6-inch diameter cylinder of 1-inch mesh chicken wire was placed in each hole for gopher protection; the holes were then refilled with

Table 2—Planting date, seed source, monthly irrigation schedule, and other treatment factors for the four planting cycles of the Coast Live Oak Regeneration Test

	Year of planting			
Cultural factors	1991-1992	1992-1993	1993-1994	1994-1995
Planting date	Late April	Late January	Late February	Early February
Site preparation	Pre-dug holes to 18 in., scalping	Litter replacement, scalping	Litter replacement, scalping	Litter replacement, no scalping
Seed source	Poly Canyon	Poly Canyon	Mixed[1]	Mixed
Acorns per planting spot	2	3	2	2
Irrigation schedule	June-Sept.	April-Oct.	June-Sept.	June-Sept.
Water per planting spot	1 gal.	0.5 gal.	0.5 gal.	1 gal.
Method of irrigation	1-gallon[2] container	Hand irrigation	Hand irrigation	4-gallon[3] container

[1]Acorns from Cal Poly Campus and from Pleasanton Ridge, Pleasanton, CA.

[2]Water for each planting spot was supplied from a 1-gallon plastic container with a small hole punched in the bottom.

[3]Water for all four treatments was supplied from a 4-gallon container fitted with four 1-gallon/hour drip emitters.

the excavated soil. A 5-ft square area containing each cluster was scalped to mineral soil in March 1992 to control grass competition.

Acorns were picked in October from a tree in Poly Canyon, about 1 mile across the campus from RTH. They were air-dried for about 10 days, then stored in plastic bags in a cold box at 38 °F. About 2 weeks before planting, the acorns were placed in plastic bags containing moist vermiculite and stored at 70-75 °F. Two pregerminated acorns with radicles approximately 1/4 inch long were sown in each planting spot during the first week of April. The control planting spots received no additional preparation. Oak leaf litter for the mulch treatment was collected from the adjacent oak stand and spread over a planting spot to a depth of about 2 inches. The litter was held in place with a 1.5- by 1.5-ft piece of chicken wire secured in place with hemp staples. Tree shelters were secured with 3/4-inch thick wooden stakes; the tops of the shelters were covered with fine plastic mesh or wire to keep out birds and other small animals.

Irrigation for the Regeneration Test was applied to each planting spot at the rate of 0.5 or 1.0 gallons per month from late spring to early fall (*table 2*). Seedling survival (*fig. 1*) and height (*fig. 2*) were measured several times from May 1992

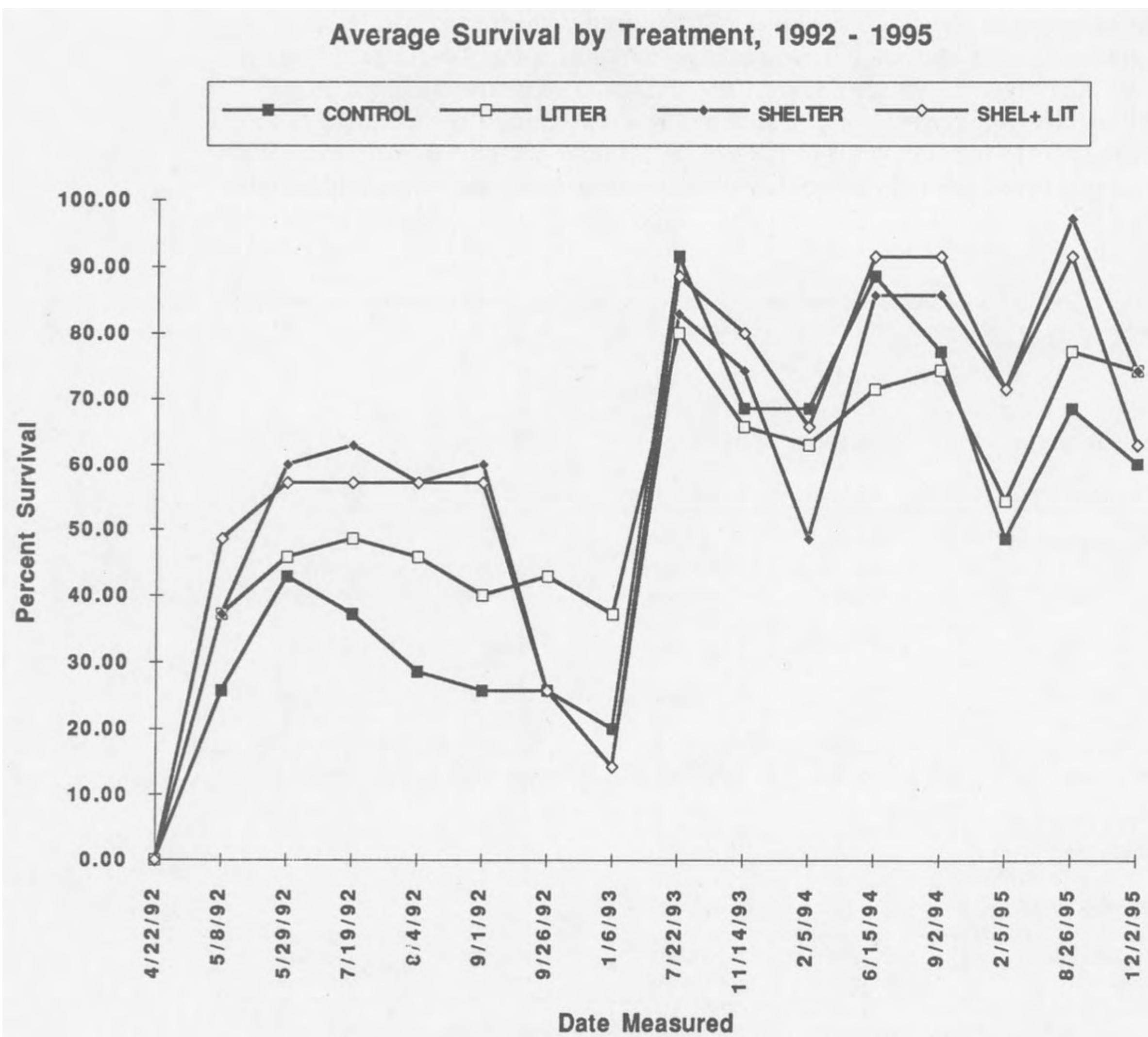

Figure 1—Percent survival of coast live oak seedlings for four planting cycles beginning in 1991. A dramatic decline in survival occurred each fall; little increase in stocking was gained after the second planting.

until January 6, 1993. All sample dates for 1992 and subsequent planting years are shown in *figures 1* and *2*.

1992-1993 Activities

Planting spots without a live seedling were replanted in late January with three germinating acorns (*table 1*). Each cluster was rescalped and the oak litter mulch replaced. Monthly irrigation of 0.5 gallons per planting spot began in late April and continued until October.

1993-1994 Regeneration Activities

All planting spots without live seedlings were replanted with two germinating acorns in late February (*table 3*). We made no effort to keep track of the acorn source for this or the following year's planting. Acorns were either from Poly Canyon or Pleasanton, California. The litter treatments were again refurbished and each 5- by 5-foot plot area rescalped.

A small irrigation study was established in March 1994 to compare two rates of irrigation (1/2 and 1 gallon per planting spot) and a nonirrigated control. Ten treatment clusters were arbitrarily dispersed throughout the Regeneration Test area with each treatment randomly assigned within a cluster. Each planting spot

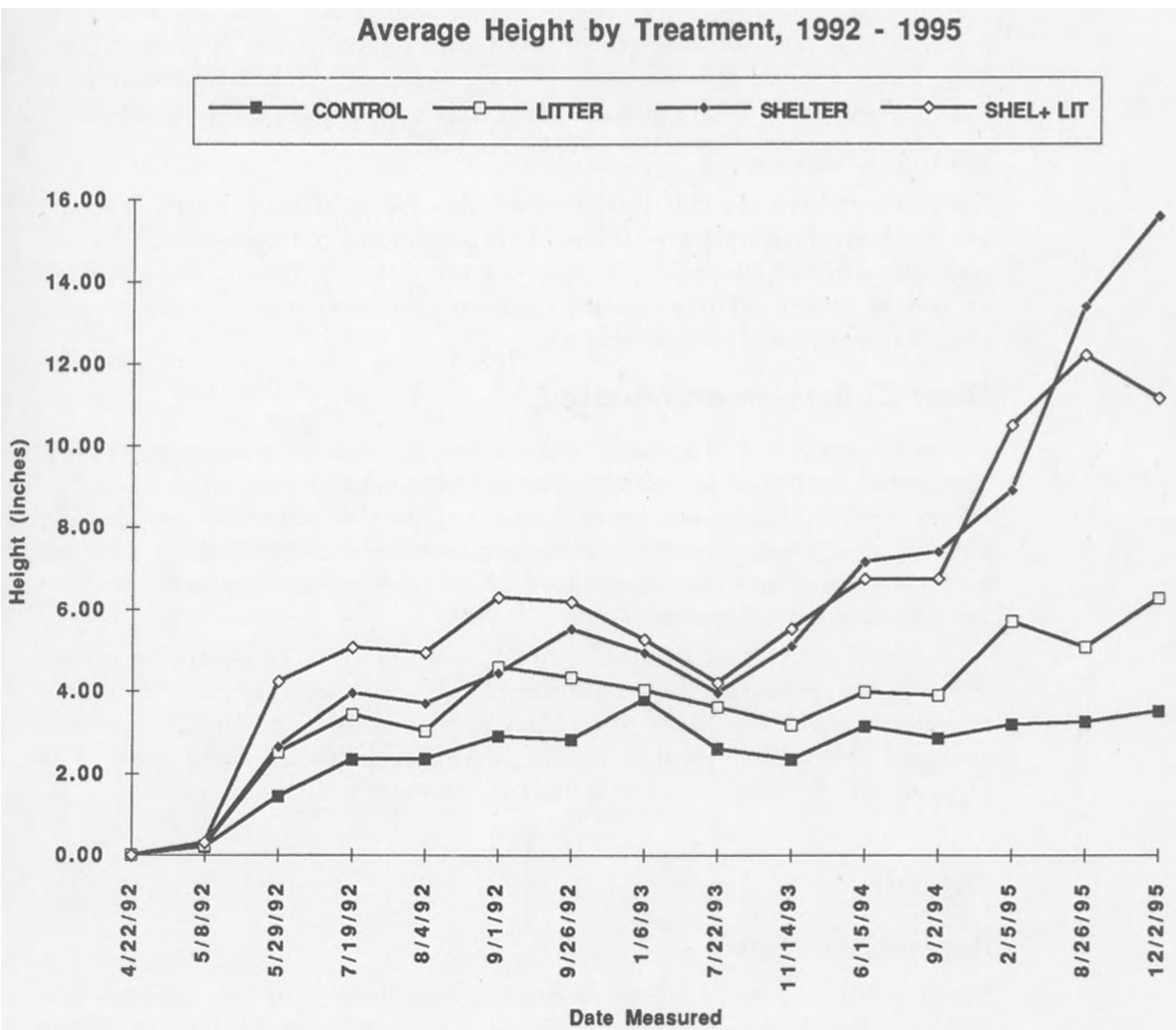

Figure 2—Average height of the coast live oak seedlings protected by tree shelters dramatically increased in 1995. However, death of several of the tallest seedlings (up to 43.3 inches tall) between August and December 1995 resulted in a drop in average seedling height for the tree-shelter-plus-litter treatment.

Table 3—Planting date, monthly irrigation schedule, and other treatment factors for the Coast Live Oak Irrigation Study

	Year of research activity	
Cultural factors	1993-1994	1994-1995
Planting date	Late February	Early February
Acorns or seedlings per planting spot	2	2
Irrigation schedule		
Water application per planting spot	June-Sept. Variable[1]	June-Sept. Variable[2]

[1]Three rates: 0, 0.5, and 1 gal. per planting spot.
[2]Nonirrigated control plots received 0.5 gal. water per planting spot on the June irrigation date.

was pre-dug with a 6-inch diameter auger, lined with chicken wire and refilled. Six-inch diameter chicken wire cylinders 12 inches tall were attached to the top of the gopher exclosures to reduce aboveground herbivory. Three germinating acorns were sown at each planting spot that were arranged in a triangular pattern, approximately 3 feet apart. The immediate plot area was scalped at planting time. Water was metered from 0.5- and 1-gallon plastic containers fitted with 1-gallon/hour drip irrigation fittings. Water was applied monthly from June to September 1994. Height and survival sampling dates are show in *figure 3*.

1994-1995 Activities

The regeneration test and irrigation study sites were replanted in early February 1995 with germinating acorns from either Poly Canyon or Pleasanton. Litter was replaced as before; however, no rescalping was done. Plant cover in the scalped areas was mostly scattered filaree (*Erodium* spp.) and was not considered a serious competitor of the oak seedlings.

Data Collection and Analysis

Treatment results for all 4 years of the work reported here are based on seedling height and survival measured periodically throughout the summer and fall (*figs. 1* to *3*). Seedling height was based on the height of the tallest live seedling per planting spot. The final evaluation for each planting cycle was usually obtained after December, with the exception of 1994-1995 when the last measurements were made in early December.

Survival data for the Regeneration Test were analyzed by logistic regression (SAS) that expressed probability of survival as a nonlinear function of age and treatment variables, with the control treatment as a reference. Height data were analyzed by multiple regression (MINITAB), again controlling for age. Plot replication differences were evaluated by a two-way analysis of variance.

Results

Regeneration Test

Seedling survival for the control and three treatments for the entire 4-year planting effort is shown in *figure 1*. Seedling emergence for the 1991-1992 cycle did not peak until mid-July for all treatments except the controls, whose survival had already begun to decline and continued to do so until replanting in 1993.

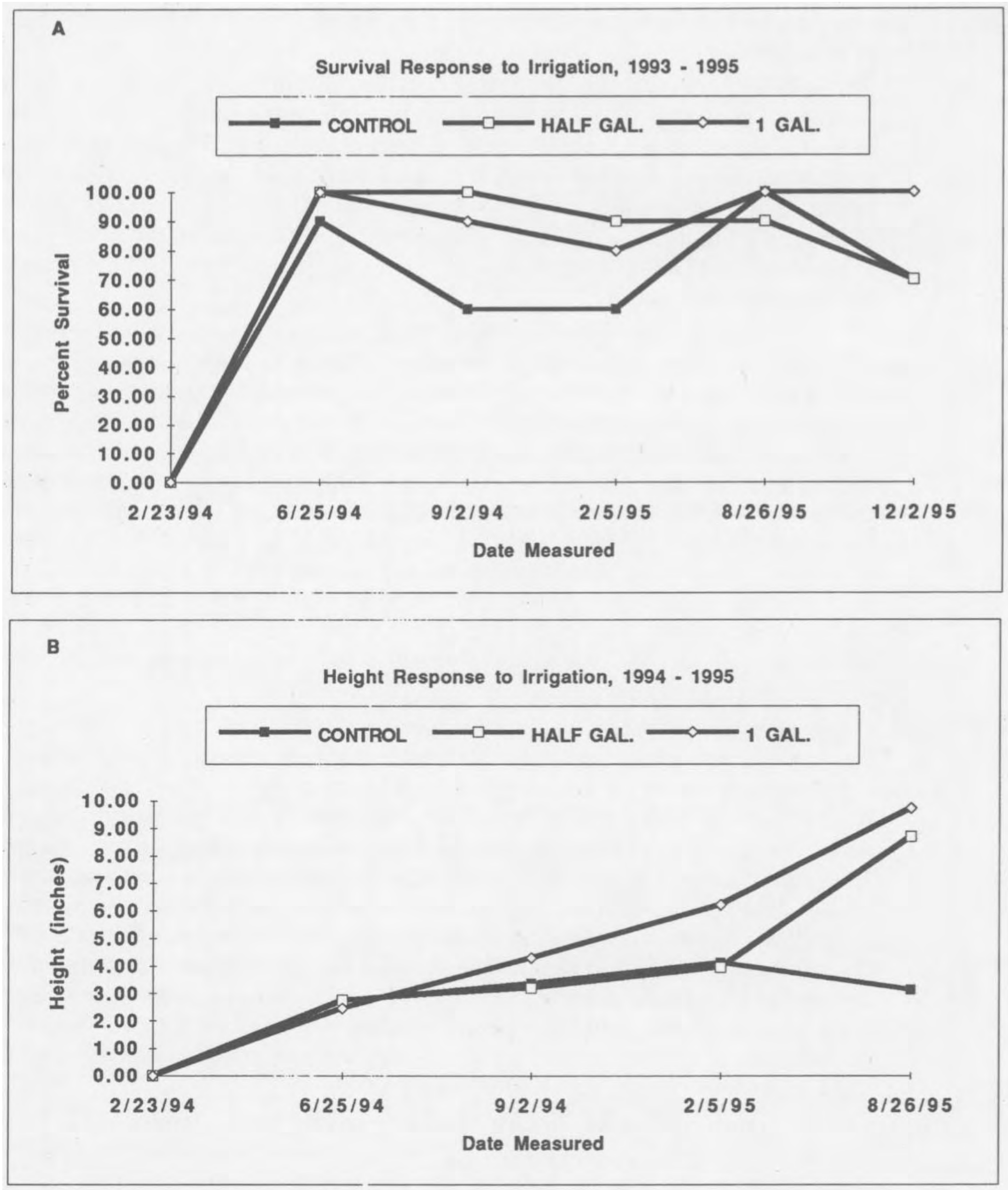

Figure 3—Percent survival (A) and average height (B) of coast live oak seedlings for the Irrigation Study 1994-1995 planting cycles. Monthly irrigation from June to October enhanced seedling height over the nonirrigated seedlings, but the effect of irrigation on seedling survival was not clearcut.

Emergence was relatively poor for all treatments, ranging from 42.9 percent for the controls to 62.9 percent for the tree shelters.

Seedling survival for the tree-shelter treatments remained constant until September 1; then there was a dramatic decline to only 14.3 percent by January 1, 1993. During this time, seedling survival for the litter treatment slowly declined, and by January 1993, it had dropped to 37.1 percent. The tree shelters initially stimulated modest height growth (*fig. 2*) over that obtained with the control and litter treatments. The high seedling mortality after September 1 did not change the height relationship among treatments. Extensive pocket gopher activity was present throughout the test area, but no seedling death was attributed to them. Most of the control and litter treatment seedlings showed signs of herbivory, and many of the tree shelter seedlings were infected with woolly aphids (*Stegophylla quercicola* Baker).

Seedling survival for the 1992-1993 cycle, which included surviving seedlings from the 1991-1992 cycle, was much higher than it was for the previous year, ranging from 80.0 to 91.4 percent on July 22. Planting in January and above-normal winter rainfall may have accounted for the increased level of survival that was enhanced by the surviving 1991-1992 seedlings. Again, there was a big decline in seedling survival for all treatments during the fall and winter (*fig. 1*). However, the seedlings in the tree shelters still maintained their height dominance.

The survival pattern for the 1993-1994 planting cycle was similar to that for 1992-1993, and 85 to 95 percent of the planting spots had live plants on June 15, 1994, except the litter treatment with only 71.4 percent. The pattern of survival was also very similar to that for 1991-1992 with a large decline after September 2. However, minimal seedling survival ranged from 48.5 to 71.4 percent, much higher than for the 1991-1992 cycle. By this time, average seedling height for the two tree-shelter treatments was about double that for the control and litter treatments and ranged from 9.0 to 10.5 inches (*fig. 2*) for the shelter and shelter-plus-litter treatments, respectively. Pocket gopher activity continued, and a few planting spots were almost completely surrounded by exit holes, but no seedling mortality was attributed directly to gophers. Most unprotected seedlings had some browsing. An extremely heavy infestation of grasshoppers was present all summer.

Seedling survival and height were measured only twice in 1995. The August 26 sampling was probably too late to obtain maximum seedling establishment, but the percent survival was still very high for both shelter treatments, ranging from 91.4 to 97.1 percent. Survival for the control and litter treatments was somewhat lower at 68.5 and 77.1, respectively. Seedling age at the beginning of 1995 varied from 1 to 3 years. However, most seedlings had died (replanting required) or were 2 years old. Logistic regression analysis indicated that seedling age, but not treatments, was a significant predictor of seedling survival ($P \le 0.01$). Again, a major decline in seedling survival occurred after early September for the shelter treatments. Although 31 of the 70 tree-shelter seedlings were infested with woolly aphids, only three of the infected seedlings died after August 26. The amount of gopher activity was amazing. In some areas on and around the test site, exit holes were only 6 to 10 inches apart.

Average height for seedlings in the shelter-plus-litter treatment also declined because some of the seedlings that died were 2 years old and more than 40 inches tall. However, seedlings for both tree-shelter treatments were about twice as tall as the control and litter seedlings. There was no significant difference between shelter treatments, or between the control and litter treatments. An ANOVA of the replications indicated that there was no significant plot effect ($P \le 0.05$).

Irrigation Study

Seedling survival for the 0.5- and 1.0-gallon irrigation treatments ranged from 80 to 100 percent for the entire test, except for a decline to 70 percent for the 0.5-gal. rate on the last sampling date in December 1995. Average percent survival for nonirrigated seedlings was generally less than for those that were irrigated (*fig. 3A*). Irrigation had a positive effect on seedling height, but there was no apparent difference between irrigation levels (*fig. 3B*).

Discussion

Attempts to artificially regenerate coast live oak in the Central Coast area of California have generally not been successful for the past several years (Plumb and Hannah 1991). Initial establishment has been excellent on some exposed grassy sites, but few coast live oak seedlings were alive 2 years later. Excluding damage and death by the many types of herbivory that have been reported on oaks, lack of coast live oak seedling survival can generally be attributed to unsatisfactory site conditions and to moisture stress specifically.

The study area had nearly uniform soils in and out of the oak stand and seemed like an ideal location to test some promising regeneration techniques. The natural expansion of the adjacent coast live oak stand over the past 80 years and the presence of advanced regeneration on the site indicated that this should be a suitable location to establish coast live oak. It was hoped that moisture stress from grass competition and low rainfall would have been counteracted by weed control, oak mulch, and/or irrigation.

Pocket gophers were a serious threat during the study, especially in 1995. The buried chicken wire exclosures seemed to provide adequate protection for the seedlings. The death of only a few seedlings could be directly attributed to gophers, and these were seedlings which gophers had extensively excavated around a planting spot. The potential threat to unprotected seedlings and advanced regeneration was demonstrated on the test site in August 1995 when a natural seedling at least 5 to 10 years old and 0.6 inches in diameter at ground level was completely severed a few inches below ground. The damage appeared to be exactly like that described by Lathrop and Yeung (1991) for Engelmann oak (*Q. engelmannii* Greene) and shows the need for long term protection where gophers are present. Unprotected seedlings have little chance of escaping gopher herbivory.

Tree shelters are used to promote height growth and reduce herbivory (Costello and others 1991, Manchester and others 1988). Both of these effects were obtained in this project. And, both tree-shelter treatments significantly enhanced average seedling height after 4 years of replanting (*fig. 2*). To the contrary, seedling survival was not enhanced by the shelters. Each year, there was a major decline in seedling survival in the fall. Ironically, the shelters produced the biggest seedlings and the lowest survival. What went wrong? Woolly aphids infested many of the these seedlings, but they usually do not cause plant death (Brown and Eads 1965). The micro environment in the shelters, which can be at least 4 to 7 °F warmer than the outside air (Costello and others 1991), apparently favored the aphid infestation.

Moisture stress would seem to be the obvious explanation for the fall seedling deaths. Irrigation was usually discontinued after September; this may have been too soon and watering probably should have been tailored to fall precipitation. Although early fall precipitation occurred in 1994, still many seedlings died during the fall and early winter. Were these deaths due to moisture stress or something else? The tree shelters promoted accelerated growth that may have ultimately contributed to the seedling deaths because of their greater water requirements.

The effectiveness of the irrigation methods was somewhat suspect because of the erratic discharge from the plastic containers and the variable amount of surface runoff that occurred from one seedling to another with hand watering. Using plastic containers in 1995 with drip emitters eliminated both of these problems. Other studies indicate mixed results with supplemental irrigation (Costello and others 1991, Gordon and others 1991), and Swiecki and Bernhardt (1991) even suggested that irrigated plants are more likely to be browsed than non-irrigated plants. In the irrigation study reported here, providing monthly amounts of either 0.5 or 1.0 gallon of water per seedling greatly enhanced height growth over that for the non-irrigated control plants (*fig. 3*). The effect of irrigation on survival was less obvious, though it was deemed to be worthwhile.

The effect of oak mulch to reduce moisture stress was not clearcut, although it did appear to enhance seedling survival at the end of the 1991-1992 and 1994-1995 planting cycles. Both Davis and others (1991) and Adams and others (1992) note the negative impact of annual grass on seedling survival. Controlling competing vegetation through a variety of methods, including scalping and mulching, can greatly improve the survival of planted seedlings (McCreary 1991). Because both scalping and oak leaf mulch were used in this test, the overall effect of scalping may have masked the effect of the mulch.

Finally, replanting this site for 4 consecutive years did not result in complete stocking. Although the overall percent survival for all treatments increased from 21.4 percent for the first planting cycle to 69.3 percent for the fourth planting cycle, this was only 7.9 percent higher than the overall survival at the end of the second planting cycle. The only significant factor affecting survival after 4 years was seedling age where the odds of survival were directly related to seedlling age (ln value of survival = 0.839 + 0.693 age). It seems reasonable to expect that seedlings that survived for 1 or more years would have a better chance of persisting another year than would a crop of new seedlings.

Conclusions

This work demonstrated that it can be extremely difficult to attain 100 percent survival (stocking) of coast live oak on a promising field site, even after repeated replanting. Little increase in stocking was gained after the second planting. It would be fiscally imprudent to repeat replanting until the cause of the late-fall, early-winter seedling death was identified.

Tree shelters enhanced coast live oak seedling growth and effectively prevented herbivory, but they did not promote greater seedling survival on this site. Late-fall, early-winter seedling death appeared to be related to moisture stress. Irrigation that was either more frequent, at a higher rate, or later in the fall might have prevented this decline in survival. Also, planting in 6- to 8-inch diameter shelters might have provided a better micro environment for the seedlings as they appeared to be crowded in the 3.5-inch diameter shelters used in this test.

Finally, although some natural seedlings near the test site have persisted and developed into saplings, it is not clear how they made it. To ensure satisfactory survival of artificial regeneration of coast live oak, we do know that it is essential to protect seedlings from above and below ground herbivory, but we are not yet certain about the level of irrigation that is needed or if irrigation is needed at all.

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Ten Years of Oak Restoration in City of Walnut Creek Open Spaces

Ralph Kraetsch

Abstract

The Oak Habitat Restoration Project began in 1991 when several individuals recognized that the oak woodlands and savannas of Walnut Creek's nearly 2,800 acres of open spaces had little natural regeneration. This group gathered volunteers who harvested acorns, planted them, and then installed tree shelters and watered the resulting seedlings. The Project soon became a unit of the Walnut Creek Open Space Foundation, which now provides most of our equipment and materials. The Project usually has 18 activity dates each year, nearly all on Saturday mornings. We usually plant 250 to 300 sites per year. About 75 percent of the sites initially contain at least one seedling from the three acorns planted in each site. At the end of the first growing season about 60 percent remain. We estimate that in 4 to 5 years about one-third of sites have become strong saplings. We have used a number of planting and maintenance methods which, over the years, have provided us with a preferred set of procedures that others may find useful.

Starting the Project

In 1989, Dick Daniel noticed that there were few oak seedlings and saplings in the Walnut Creek Open Spaces. He planted about 100 sites in a small fenced area in the open space and found very good success. During 1990, I made the same observation of lack of oak regeneration, and in the spring of 1991 Dick and I, together with Walnut Creek's newly hired Open Space Superintendent, Dan Cather, recruited volunteers for the Oak Habitat Restoration Project. The Project began with about 50 volunteers who typically attend 4 to 8 of our 18 activities per year.

We are fortunate that the City of Walnut Creek encourages our work and trusts the Project's judgment in restoration activities. This has enabled us to work with different restoration methods over the years until we found the methods we believe are well adapted to our warm and moderately dry climate.

The City provides storage space for our equipment and materials. The Project is now an activity of the non-profit Walnut Creek Open Space Foundation which funds most of our necessary equipment and materials. Vehicle needs are provided by volunteers. Grants from the California Native Plant Society, Chevron, and California ReLeaf and the California Department of Forestry and Fire Protection were important to our success in several of our early years. Walnut Creek is located 22 miles directly east of San Francisco. In 1974 and 1975, the City acquired about 1,800 acres in four open space parcels on its periphery.

The open space now totals over 2,700 acres. These hilly oak woodland, savanna and chaparral areas were intensely grazed for many years prior to 1975, and this continued until 1990 when about 425 acres in Shell Ridge were withdrawn from grazing. In 1997 about 375 acres of Lime Ridge were withdrawn. These are the areas in which we have done most of our planting.

Procedures

Acorn Harvest

Our Project year begins in September with the acorn harvest. The crop varies widely from year to year and sometimes from species to species. We have three oak species, blue oak, valley oak and coast live oak *(Quercus douglasii, Q. lobata,* and *Q. agrifolia*) and we harvest only from open space trees to maintain local genetic integrity. In years with small acorn crops there is often a higher proportion of insect damaged acorns so we tend to pick earlier, before maximum predation occurs. We continue picking as long as acorns hold on trees, usually after three harvest dates. We provide volunteers with the following acorn harvest directions: Equipment needed: 1 quart plastic collecting bags, swab pen for labeling bags, hook pole for harvesting acorns higher in tree (optional; use especially in years with poor acorn crop), larger bag for holding 1 quart bags.

1. Collect acorns only from a tree, never from the ground.

2 . Remove caps and check acorns for damage before placing them in a collecting bag. Reject any acorn with damage to the base of the acorn, usually caused when removing the cap from an immature acorn. Also reject acorns with evidence of insects, bruises, cracks, misshapenness or very small. In years with poor acorn crops it may be necessary to keep some acorns with bruises or minor insect damage.

3. Use 1 quart collecting bags, no more than 100 acorns per bag, and be sure to label each with oak variety, date and general location.

4. Do not mix oak varieties in one bag. If you're not sure how to identify different varieties, ask!

We store acorns until planting in quart plastic bags, top partly open, in our refrigerator, just above freezing to retard sprouting and mildew. We dry the acorns monthly during storage to retard mildew, a somewhat laborious process. We have found a significant difference in storage capability among our three oak species. Blue oak acorns sprout radicles and often develop mildew after just 3 to 5 weeks in storage. Valley oak acorns tend to sprout radicles 6 to 8 weeks after harvest, and are slower to develop mildew. Coast live oak acorns rarely develop radicles before 8 weeks, and many do not sprout for several months after harvest. Some of our 1999 coast live oak acorns stored in our refrigerator in partly open plastic bags within a closed heavy carton sprouted successfully when planted in midsummer of 2000. Similarly, many coast live oak acorns collected in 2000 were viable in July 2001.

Planting

We begin planting after fall rains have moistened the soil to 8 to 10 inches and usually have five planting dates between late November and mid-January. We provide teams of two volunteers with the following directions for planting 10 sites. Materials needed: 10 mulch mats, 40 mulch mat staples, 10 aluminum tags, 10 36-inch survey flags, ball point pen, trowel, clipboard with pre-numbered data sheet and procedures sheet, bag with 30 acorns, floral shovel. Units of 10 screen cylinders have been previously placed in the field.

1. Select a site at least 50 feet from other plantings. Site should be on a sufficient slope that there will not be standing water during heavy rain periods.
2. With the shovel or other tool remove grass and weeds from an area 3+ feet square.

3. Dig a hole in the center of the cleared area about 8 inches deep. Keep the dirt within the cleared area for refilling the hole.

4. Place a screen cylinder in the hole, at least 6 inches deep and fill inside the screen to about 1 inch below the surface level. Fill outside the screen to surface level. Tamp the filling to reduce future compaction, a major cause of failure due to acorn rot from water accumulation in a compaction "lake."

5. Place three acorns inside the screen, on their side, near the screen, points toward the center. Make a hole for any root (radicle) showing from the acorn. Fill inside the screen to ½ to 1 inch above the surface level.

6. Open the center slot of a plastic mulch mat about 1 inch on each side so the slot is just large enough to slip over the screen. Install the mat over the screen, shiny side up. Fold over the corners of the mat 3 to 4 inches and staple each corner through the folded layers of plastic.

7. With a ball point pen firmly write the site number on an aluminum tag (00-123, for example) using fairly large letters and attach the tag at the top of the screen. The "00" identifies the year of acorn harvest. The site number is preassigned on your data sheet.

8. Fill out the data sheet.

9. Pinch together the upper 1_ inches of the screen and fold this over about 45 degrees from vertical. DON'T FOLD TIGHTLY! We have to get back inside the screen in the spring to weed and install treeshelters.

10. Insert a survey flag through the three layers of screen. Don't bend the flag wire. Extend the flag as high as possible above the screen so we can locate the site after the grass grows tall in the spring.

Spring Maintenance

Spring maintenance includes inspection of winter plantings, weeding inside screen cylinders and installing treeshelters on seedlings. Seedlings begin to emerge in mid-March. Some delay until early May, depending, we believe, on the planting date, acorn variety, depth of planting and amount of sun on the site. We weed all sites as we inspect them, whether or not a seedling can be found. Discovering new seedlings is a highly satisfying activity! We provide teams of two volunteers with the following list of procedures for spring maintenance and treeshelter installation.

Materials: clipboard with data sheet and procedures list, pen, swab pen, trowel, 10 bird nets, small sledge hammer (10 Tubex treeshelters, 10 rebar posts and water are already in the field).
1. At a site, remove the flag, open the screen cylinder and look and feel for seedlings. You will often see

mostly grass and weeds. Remove them. Oak seedlings are stiff and like a short brown blunt toothpick when they first emerge. Later a couple of small leaflets show.
2. If no seedling has yet emerged, or you're unsure whether something is actually a seedling, close the screen and replace the flag. We will recheck the site later in the spring.

3. If you find a seedling, after removing the grass and weeds, use a trowel to loosen the soil around the inside edge of the screen. If the soil is too firm, soften with some water. Of course, no damage to the oak seedling! Rotate the treeshelter into the soil at least 2 inches.

4. Push a rebar post through the plastic ties on the treeshelter and into the ground (use a hammer if necessary) below the top of the treeshelter if possible. Tighten the plastic ties. Add some water to settle the soil. Put a bird net over the treeshelter. Bend the top of the screen cylinder as necessary to minimize the space between the cylinder and the treeshelter to exclude rodents and lizards.

5. Complete the data sheet with the site number and seedling information. Dittos or arrows are fine for other notes.

6. Use the swab pen to place a 6+inch number reflecting the year of acorn harvest on the treeshelter visible from the nearest service road direction. This helps us identify which seedlings need to be watered during the summer.

The bird net is used to exclude birds who often perch on the treeshelter and occasionally fall in, killing themselves and usually any seedling present. The screen cylinder is left in place to protect the tender root system from rodent predation. The Tubex treeshelters serve several purposes. Most important, they conserve moisture by recirculating daily condensation inside the shelter back down to the seedlings. The shelter also focuses summer watering on the seedling root system for deeper watering rather than spreading widely with shallow soil penetration. A third very important function of the treeshelter is discouraging predation by wildlife. We have found two sources of deer predation, browsing and antler rubbing on saplings in the fall.

We leave treeshelters on the plantings as long as the shelters hold together, many nearly 10 years at this time. Treessentials of Mendota Heights, MN (800-248-8239) is our supplier for the Tubex treeshelters, the plastic mulch mats and staples, as well as the small bags of slow release fertilizer we sometimes use in plantings.

Summer Watering

We try to water seedlings for two summers to provide moisture during the critical summer dry period in their early years. We have no field source of water for piped irrigation, so we must carry water to the seedlings. Prior to the announced watering day we fill 1 and 1½ gallon plastic jugs and truck them to the planting area where they are dropped along service roads near the seedling sites. Volunteers then carry the water jugs to the seedlings, placing about ½ gallon in each treeshelter. During the first watering sessions we inspect the plantings that have not yet
shown a seedling. If a seedling does not show by June we recover the screen cylinder for

reconditioning and reuse. At the end of the watering season we're already in the next acorn harvest.

Learning Experiences

Our learning experiences from these 10 years of restoration work are categorized into treeshelters and posts, screen cylinders, grazed area planting, fire effects and volunteer programs.

Treeshelters and Posts

We have experimented with various materials for the treeshelters, but have always returned to the stiff preformed plastic treeshelter under the Tubex brand. One year we used a corrugated plastic material that is shipped flat and shaped into a treeshelter in the field. In parts of the country with cold winters this system is reported to have advantages. In our area these treeshelters begin to deteriorate within 2 to 3 years and form a fragmented mess that is difficult to clean up. We have also experimented with shelters made of heavy film. These are short, require wire exclosures and also deteriorated within 2 years.

In our early years we tried all available lengths of Tubex treeshelters, from 1 to 6 foot lengths. We no longer use the 5- and 6-foot shelters. Their original purpose was to protect seedlings from cattle browsing. We have found that seedlings have difficulty overtopping the taller shelters in our lower rainfall environment. The 1, 2 and 3-foot treeshelters require that we install exclosures to protect against deer browsing. Thus, the 4-foot treeshelters best satisfy our local needs.

In our first years we used T-bar fence posts to stabilize treeshelters. In order to reduce costs we then tried oak and redwood posts. The best of them rotted within 4 years. We have settled on 3/8-inch diameter rebar posts and find them cheaper than wood. In addition they can be recycled indefinitely.

Screen Cylinders

We tried a number of materials to build screen cylinders to defend the acorns from rodent and insect predation before settling on 24-gauge hardware cloth (screen). We purchase this material in 100-foot rolls of 2 foot width, cut it into 20 inch lengths and wire the resulting pieces into the 2 foot by 6 inch diameter cylinders. Lighter weight materials were too easily penetrated by our abundant ground squirrels.

Planting In Grazed Areas

We currently plant only in areas which are not grazed. In our early years we tried planting in grazed areas with disappointing results. The cost in materials and volunteer time is about double the cost for planting in ungrazed areas. Our method was to install a planting site as described earlier and add a 3½ -foot diameter exclosure of 5 foot welded wire fencing stabilized with 2 or 3 rebar posts of ½-inch diameter. This is usually satisfactory where there are plenty of trees for cattle rubbing, but in areas with fewer trees our plantings became the principal rubbing target and were often severely damaged.

Fire Effects

Our single experience with fire 3 years ago showed it quite damaging to our plantings, but the effect can be short term. Heat melted the plastic treeshelters against the young oaks and killed the stems. However, we found that four of five plantings resprouted and grew rapidly from the undamaged root system.

Volunteer Programs

Volunteer recruitment has been a challenge over the years. The best sources have been members of our sponsoring Walnut Creek Open Space Foundation, the local Volunteer Center, open space kiosk signs and publicity in the local newspaper. Occasional "Volunteer Day" programs sponsored by the City of Walnut Creek have been helpful, and one was the largest source for our beginning volunteer group. Volunteer retention is also a problem. We have a core group of 12 to 15 who have been frequent participants over the years. Others come once or twice per year and still others find the activities too strenuous or not as interesting as they anticipated. A few others, largely the younger group, find new parenting or changed work responsibilities become higher priorities. Or they move out of the area. Teenage participants are welcome, but only a few attend more than once, usually to satisfy a high school community service requirement. The best volunteers are the newly retired who have not yet fully committed their time.

We publish a simple monthly newsletter, *Oak News,* which announces coming Project activities, notes volunteers present at recent field efforts, and comments on oaks, other native plants and general open space programs. We find the newsletter useful as an activity reminder, as an educational tool and to publicize the program to City officials and others.

Future Programs

In our early years we prepared for planting by dropping bundles of 10 screen cylinders at the 3 entrances to the Shell Ridge Open Space planting area. We found that areas distant from open space entrances received much less attention from volunteer planters than areas closer to the entrances. In recent years we have dropped the screen cylinders in the field at a number of locations closer to the target planting areas with much improved planting distribution.

We are planning to try planting without screen cylinders in areas that are more difficult to reach so that volunteers will not need to carry full kits of materials long distances. This will involve planting about 20 acorns around a marker we can identify later. Then, after the grass dries we will return to these locations and search out any seedlings for installing treeshelters. Experiments with this method in past years haven't been successful. We will need to be especially careful to plant in areas without ground squirrels.

As noted earlier we have done most of our planting in the ungrazed areas of the City's open space. Many plantings in grazed areas have largely been severely damaged by cattle. In the future we hope to fence small plots, perhaps 20 to 30 foot squares, and plant several sites within each plot.

Results

We have recently made field checks of all surviving planting sites in order to compare our actual success with our estimates of success. Data from our first 6 years of planting in Shell Ridge Open Space is in poor condition so detailed analysis is not possible. We found 547 living sites from those plantings.

Assuming an average of 300 sites planted per year yields a 30 percent success rate.

Analysis of sites planted during November 2000 to January 2001 with acorns harvested the previous September has provided much more useful results that will help direct our future planting methods and data recording.

Conclusions

The preceding data analysis suggests several additions to our data recording. Topographic aspect of the planting site, soil character and possibly treeshelter diameter may help explain why some plantings are more successful than others. We can conclude that blue oaks, despite their abundance as living trees, have more trouble regenerating. We should plant four rather than three acorns in each blue oak site, and plant them early in the season, before mildew attacks elongated radicles.

Analysis by planting date and correlation with rain periods may help increase efficiency of planting. Our trial and error approach through this decade has led us to conclude that most of our current procedures are effective for a regeneration program of our size and budget in our environment. We welcome suggestions that may improve our results, and we will be happy to discuss our methods in more detail and provide field visits for those interested in our oak regeneration activities.

Native Oak Tree Planting Project

This winter, the City of Roseville is undertaking a native oak tree planting project. Using a mixture of acorns, seedlings, and container plants, 7,700 native oaks will be planted in several open space areas throughout the City for a total of over 30 acres (see map on reverse). Roseville's urban forest will see tremendous benefit from this project with ***increased wildlife habitat enhancement***, ***CO_2 reduction***, ***air quality improvement***, and ***reduced stormwater runoff.***

Why is the City undertaking this project?
Enhancing and growing Roseville's urban forest and providing additional recreation and aesthetic value for the residents of Roseville is an important goal of the City's Parks & Recreation Department. The City has a Native Oak Tree Ordinance that requires mitigation, or replacement of native oak trees that have been removed due to development projects. Onsite replacement is the preferred method, however in some cases where onsite plantings are not feasible, the developer may pay an in-lieu fee to the City's Native Oak Tree Mitigation Fund.

How was this project planned and by whom?
In March of this year, the City issued a Request For Proposal (RFP) open to restoration and landscape contractors. This RFP was developed with the help of a qualified restoration biologist with the goal of identifying suitable sites and appropriate numbers of oak trees to be planted at each location. Through this process the City identified seven priority planting sites within the City's Open Space and Park areas. Sites and planting numbers were recommended based on soil surveys, the availability of irrigation water, existing open space canopy, and aesthetic value for residents. EcoSystems Restoration Associates, an experienced restoration contractor, was awarded the project and is being overseen by the City's Urban Forester, Michael Neumann, who is also experienced in oak woodland restoration.

How long will the project take to complete?
Residents living near the affected open space areas may see workers planting through January 2008. After the initial planting, maintenance, including irrigation and weed control, will occur during the three-year establishment period, followed by two years of monitoring the condition and health of the seedlings.

Why so many trees?
Over the years, several of the planted trees may not survive so higher quantities of trees planted means a higher survival rate overall. The majority of the trees to be planted are seedlings, and survivorship of 80% at the end of the five years is typical for trees of this size. Seedlings were chosen for the majority because the larger the tree is at planting, the longer the establishment period. While larger-sized container plants offer greater height and width at planting, they are much more expensive and the differences in initial size are generally lost following establishment. Studies demonstrate that trees from larger stock have a decreased growth rate when compared with those of smaller stock. Other reasons for oak tree mortality include herbivory by rodents and other mammals, competition from non-native grasses, and vandalism.

Is all the irrigation really necessary?
To increase the tree survivorship rates, we are supplementing the plantings with temporary irrigation. Seedlings grown under a well planned irrigation program have been shown to have lower mortality, better overall health, and more robust growth as compared to their non-irrigated counterparts. The white irrigation pipes may be painted to blend with the surrounding environment if the existing grasses and vegetation do not cover the pipes on their own by Spring 2008. The irrigation will be completely removed by the end of the five year project.

How were residents notified of this project?
During the week of October 22nd over 1,200 postcards with project information were mailed to residents within the vicinity of the planting sites. An article has also been posted on the City's home page since early October. In addition, an article was published in the current issue of *Roseville Reflections*, the City of Roseville newsletter, which comes as an insert in the Press Tribune and is also available at various City facilities.

How is this project funded?
This planting project is funded by the Native Oak Tree Mitigation Fund, which collects in-lieu fees paid by development projects where onsite replanting of native oak trees is not feasible. Since it's inception in 1993 a significant amount of mitigation funds have been collected. By law, these funds can only be used for native oak tree mitigation. There will be no fiscal impact to the City's General Fund.

How can residents help?
These seedlings are being planted to restore and replace the habitat of animals disturbed during development of new communities. Planting these trees will benefit both animals and residents of the community. The project will be more successful with the support and protection of residents who frequent the planting areas. Vandalism of the irrigation system and seedlings could destroy the trees, which would require replanting new seedlings and additional maintenance and monitoring. Please report any vandalism activities to the Parks Division at the number below.

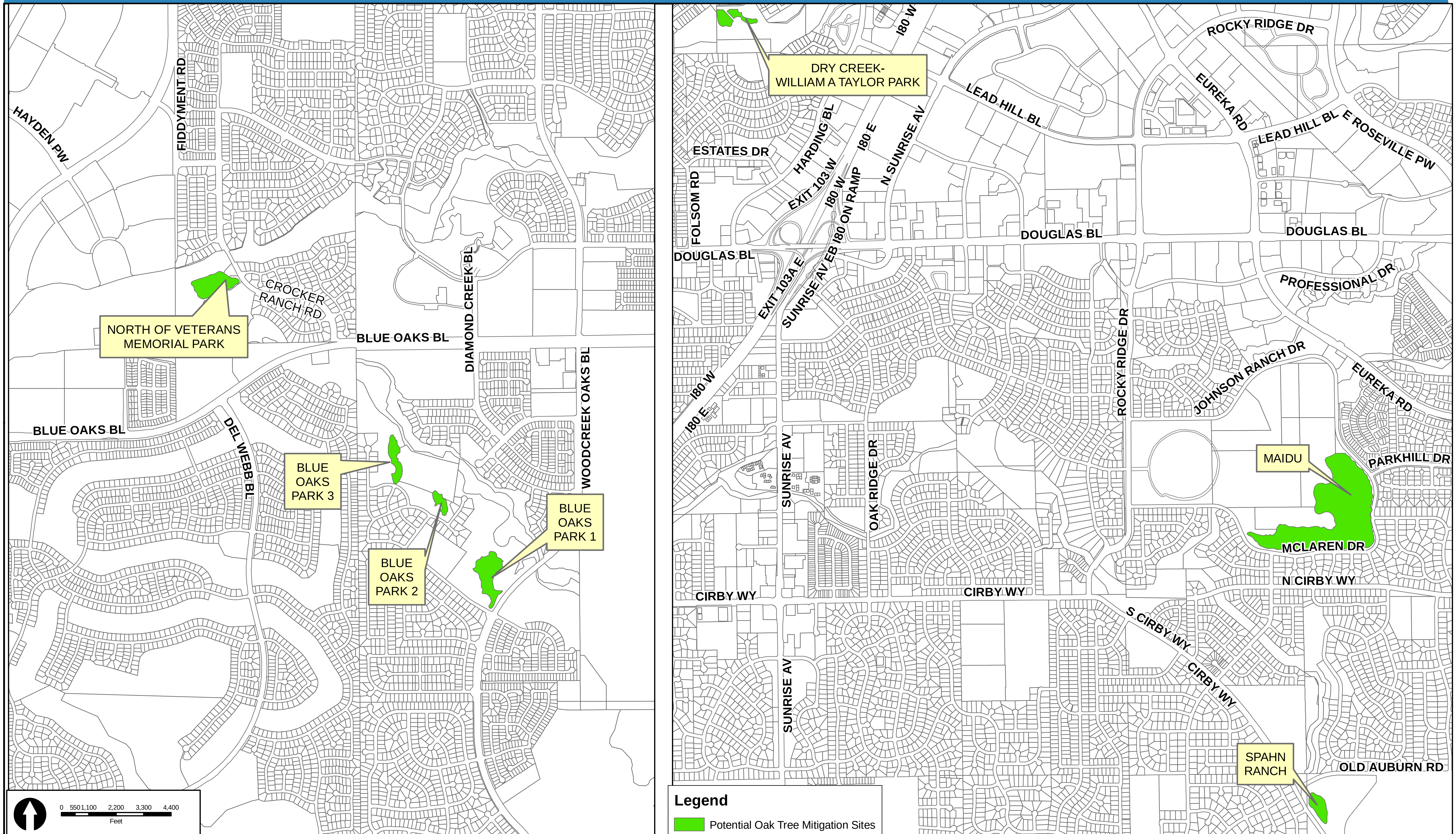
For more information, contact the Parks & Recreation Department at 774-5748 or
www.roseville.ca.us/parks.

CITY OF ROSEVILLE CALIFORNIA

CITY OF ROSEVILLE CALIFORNIA

Tree Mitigation Fund Planting Sites

March 7, 2007



Native Oak Tree Planting 2007-08

During Planting

This photo shows the Maidu Regional Park planting site during the planting phase.

The white irrigation pipes visible in this photo may be painted if the vegetation does not cover them naturally.

Following planting, the flag markers and piles of soil and mulch will be removed.

Post Planting - 6 months

This photo shows another site within six months of the initial planting. Vegetation has grown up around the irrigation pipes.

Note: The green plastic tree shelters shown in this picture will not be used in Roseville's tree planting project.

Post Planting - 3 years

This photo shows another site three years following the planting.

CITY OF ROSEVILLE CALIFORNIA

Factors Limiting Recruitment in Valley and Coast Live Oak[1]

Claudia M. Tyler,[2] Bruce E. Mahall,[3] Frank W. Davis,[4] and Michael Hall[5]

Abstract

The Santa Barbara County Oak Restoration Program was initiated in 1994 to determine the major factors limiting recruitment of valley oak (*Quercus lobata*) and coast live oak (*Q. agrifolia*). At Sedgwick Reserve in Santa Barbara County, California, we have replicated large-scale planting experiments in four different years to determine the effects of cattle and other ecological factors on oak seedling establishment in oak savannas and woodlands. In 33 large experimental plots (50 x 50 m) we planted acorns collected from *Q. lobata* and *Q. agrifolia* on the site. Fifteen of these large plots are controls, open to grazing, fifteen exclude cattle with the use of electric fence, and three are ungrazed in large ungrazed pastures. Within the plots, experimental treatments included: 1) protection from small mammals such as gophers and ground squirrels, 2) protection from large animals such as cattle, deer, and pigs, and 3) no protection from mammalian grazers. In winters 1997, 1998, 2000, and 2001, we planted approximately 1,000 acorns of each species. Results confirm that seed predation and herbivory by small mammals are a significant "bottleneck" to oak seedling recruitment on the landscape scale. Comparing results among years indicates that lack of late winter rainfall can significantly reduce oak emergence and establishment. Survivorship of protected acorns and seedlings is comparable in grazed and ungrazed areas.

Introduction

Oak woodland and savanna habitats, among the most diverse communities in North America, have suffered significant losses in the past century (Bolsinger 1988), primarily due to agricultural conversion and urban development. In addition, natural regeneration of the keystone species (in the genus *Quercus*) of these systems appears to be insufficient to maintain current populations. Many reasons for this lack of recruitment have been proposed including: 1) intense browsing of saplings and seedlings from large mammals (both deer and introduced cattle) (Griffin 1971); 2) acorn predation by cattle, deer, ground squirrels and others (up to 100 percent predation in some cases) (Borchert and others 1989); 3) trampling by cattle (Griffin 1973); 4) underground root attack from fossorial rodents (primarily gophers); 5)

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[1] An abbreviated version of this paper was presented at the Fifth Symposium on Oak Woodlands: Oaks in California's Changing Landscape, October 22-25, 2001, San Diego, California.

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competition with exotic annual grasses for water (Danielson and Halvorson 1991); and 6) soil compaction by cattle (Braunack and Walker 1985).

More than 75 percent of oak woodland in California is grazed by cattle, making cattle the most pervasive anthropogenic influence on these ecosystems. Thus, the effects of cattle grazing must be a central theme in a comprehensive investigation of natural regeneration and restoration in today's oak savanna/woodland communities. Although cattle have been implicated as a primary cause of the failure of natural oak recruitment (Griffin 1973), their effects are clearly not straightforward. Even in areas that have not been grazed by cattle for almost 60 years (e.g., the U.C. Hastings Reserve), there is still a lack of significant oak regeneration.

The Santa Barbara County Oak Restoration Program was initiated in 1994 with the goals of determining the major factors limiting recruitment by valley oak (*Quercus lobata*), and coast live oak (*Q. agrifolia*). and identifying cost-effective techniques for large-scale oak restoration in grazed savannas. The primary foci of this program are the effects of cattle, small mammals, and interannual weather variations. Here we present preliminary results from four years of experimental plantings in this long-term oak regeneration program.

Methods

Research was conducted on the Sedgwick Reserve, a 5,883-acre (2,382-ha) ranch located in the Santa Ynez Valley in Santa Barbara County, California. The climate is Mediterranean, with hot dry summers and cool wet winters. Mean annual rainfall is 397 mm. Total precipitation (as recorded at the nearest National Weather Service recording station) for the rain years 1996-1997, 1997-1998, 1998-1999, 1999-2000, and 2000-2001 was 298 mm, 828 mm, 309 mm, 387 mm, and 649 mm, respectively. Under a cooperative grazing agreement with the College of Agriculture at California Polytechnic University, San Luis Obispo, students and faculty from Cal Poly maintained and cared for the cattle herd at Sedgwick, and assisted with the application of grazing treatments in our experiments.

Our large experimental plots were 50 x 50 m. Fifteen of these large plots were controls, open to grazing, and fifteen excluded cattle with the use of electric fence. These plots were established in 1995. They were chosen as pairs, with one randomly selected to be fenced to exclude cattle. In addition, three single 50 x 50 m plots were established in 1996 in three large ungrazed areas.

Within the plots, experimental treatments included: 1) protection from small mammals such as gophers and ground squirrels *(fig. 1a),* 2) protection from large animals such as cattle, deer, and pigs *(fig. 1b),* and 3) no protection from mammalian grazers *(fig. 1c)*. Large cages were constructed of 4 ft high, 2 x 4 inches mesh galvanized wire (12 gauge); they were round (diameter = 18 inches) and supported at one side with a 5 ft t-post, and at the other side with a 4 ft rebar. Smaller cages to exclude small mammals were cylinders constructed of 3 ft high hardware cloth (mesh size = 0.5 inches); they were sealed at both ends with aviary wire. In positions with cages (small mammal exclusion), the cages were set 12 inches into the ground. Each of these treatments was replicated five times within each plot for each species.

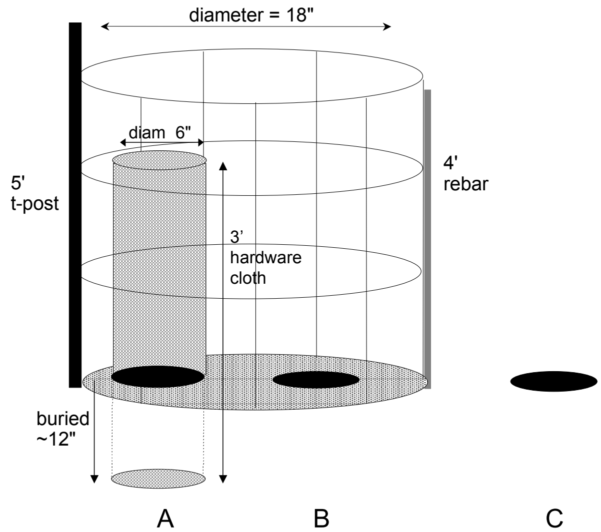

Figure 1—Treatments used for acorn plantings. A: caged and fenced to prevent grazing and herbivory by both large and small mammals (this treatment is referred to as "no rodents"). B: fenced to prevent grazing by large animals. C: open. These treatments are replicated in both 1) plots that are grazed by cattle and 2) plots that are fenced to exclude cattle.

Following the onset of consistent seasonal rains (December or January), at each planting location holes were augured to a depth of 12 inches, soil replaced and two viable acorns planted 1-2 inches below the soil surface. We planted acorns collected from *Quercus lobata* and *Q. agrifolia* on the site in the fall of the same year. Prior to planting, acorns were placed into buckets of water. Acorns that floated were discarded; we planted only acorns that sank and appeared viable. Acorns and seedlings did not receive supplemental watering through artificial irrigation.

In winters of four years, 1996-1997, 1997-1998, 1999-2000, and 2000-2001, we planted approximately 1,000 acorns of each species. In 1996-1997, and 1997-1998, we planted in all 33 plots. In January 1998 (El Niño year), the trees in the middle of two of these plots were blown over. The broken trunks and downed large limbs made future planting in these plots unfeasible. Because the plots are paired, we removed the two sets of plots (total of four) from additional planting experiments, reducing the number of plots in 1999-2000, and 2000-2001 to 29: 13 fenced, 13, unfenced, and 3 in large ungrazed pastures.

Results

2000-2001 Planting

Grouping all treatments, 17 percent of *Q. lobata* seedlings emerged, and 26 percent of *Q. agrifolia*. There were striking differences in emergence rates among experimental treatments *(fig. 2)*. The highest seedling emergence was found in locations that were protected from both rodents and large grazers. It appears that there were no differences in initial emergence rates in large grazed versus ungrazed plots, indicating that cattle grazing did not affect emergence of oak seedlings. At present, grouping all treatments, there are 405 newly emerged seedlings from the 2000-2001 plantings (160 *Q. lobata* and 245 *Q. agrifolia*).

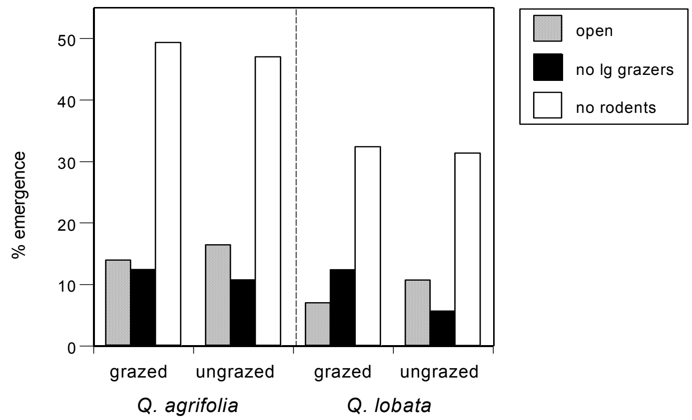

Figure 2—Total percent emergence of seedlings planted in 2000-2001 with various levels of protection from herbivores. Data are from May/June 2001.

1999-2000 Planting

The highest emergence and survivorship has been for seedlings that are protected from small mammals *(fig. 3)*. However, mortality of 1-year-old seedlings, especially *Q. agrifolia*, has occurred over the past year. It appears that there was relatively higher mortality for both species in the large ungrazed plots. In terms of actual seedling numbers, there are currently 337 established 1-year-old seedlings (273 *Q. lobata*, and 64 *Q. agrifolia*). Fifty percent of these seedlings are in the treatment protected from rodents.

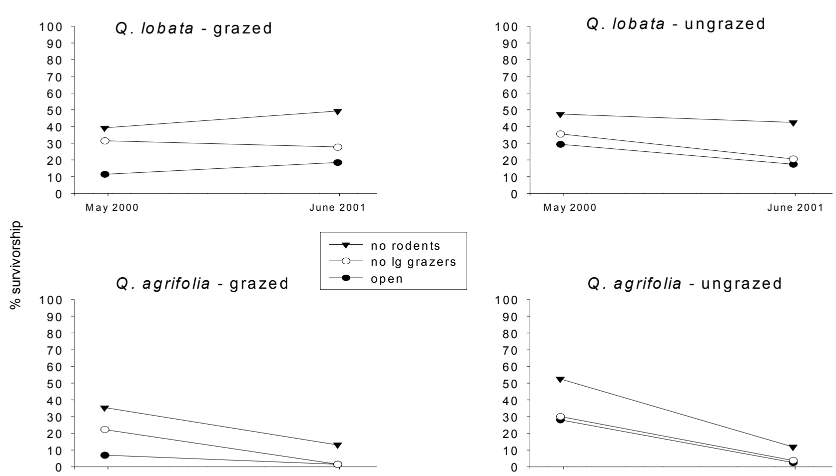

Figure 3—Percent survivorship of 1-yr-old seedlings (planted in 1999-2000) in large plots grazed by cattle, vs. those fenced to exclude cattle. Data are totals for three experimental treatments *(fig. 1)* for two sampling dates

1997-1998 Planting

The highest seedling/sapling establishment rates are for those protected from small mammals *(fig. 4)*. In nearly all treatments highest mortality thus far appears to have occurred in the first season after emergence. However, it is interesting to note that there was higher mortality for both species in the plots that have been ungrazed (see "no rodent treatment," *fig. 4)*. In terms of actual seedling numbers, there are currently 526 established three-year-old seedlings (300 *Q. lobata*, and 226 *Q. agrifolia*). Sixty-seven percent of these seedlings are in the treatment protected from rodents.

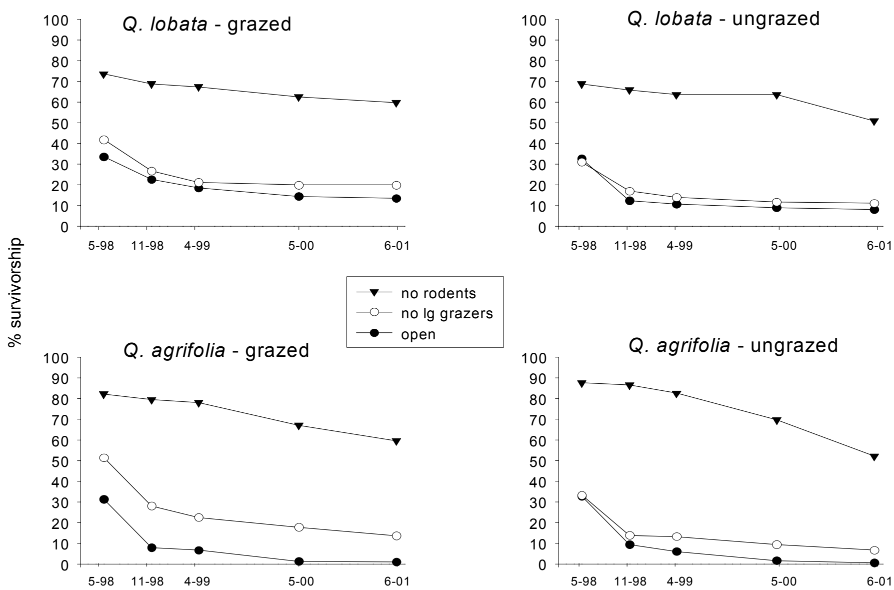

Figure 4—Percent survivorship of 3-yr-old seedlings (planted in 1997-98) in large plots grazed by cattle, vs. those fenced to exclude cattle. Data are totals for three experimental treatments *(fig. 1)* for five sampling dates.

1996-1997 Planting

Out of 2,112 acorns planted in 1996-1997, a total of 13 four-year-old established seedlings have survived, or less than 1 percent of each species planted *(table 1)*. There are presently 4 four-year old *Q. agrifolia* seedlings, and 9 four-year old *Q. lobata*. Our results suggest that the treatment that was most successful in terms of oak establishment was that which excluded small mammals. There are no seedlings surviving from the 1996-1997 planting that were in the open.

Table 1—*Percent survival of seedlings of each species in each age class to June 2001 (all treatments combined). No acorns were planted in 1998-1999 because acorns were unavailable.*

	Planting year				
	1996-1997	1997-1998	1998-1999	1999-2000	2000-2001
Quercus lobata	0.9	21.6	-	29.4	17.2
Quercus agrifolia	0.4	16.3	-	6.9	26.4
No. planted per sp	1,056	1,386		928	928

Discussion

Results from our four large-scale planting experiments indicate that several factors play a role in limiting or promoting seedling recruitment of oaks, most notably rainfall and herbivory by small mammals. Abundant rainfall in late winter, as seen in the El Niño year 1997-1998, can significantly enhance emergence and survivorship, while very low rainfall, as seen in 1996-1997, results in low seedling numbers. The effects of annual variation in precipitation levels, which are directly related to soil-moisture levels, on oak establishment have been described in previous studies. Griffin (1971) proposed that reduced rainfall greatly reduced establishment of blue and valley oak in central California. Plumb and Hannah (1991) concluded that low rainfall was the primary cause for poor success in regeneration work with coast live oak. In our study, which aims to determine cost-effective methods for oak restoration on a large landscape scale, plants have not been artificially watered because a) irrigation is expensive and may be economically infeasible on a large scale, and b) the long-term survivorship of saplings following weaning of supplemental watering is unknown. However, it is clear that adequate rainfall in the first year after planting will directly affect the success of restoration efforts.

As observed in all four planting years, at all planting sites, in both grazed and ungrazed plots, and for both oak species, seed predation and herbivory by small mammals (most likely gophers and ground squirrels, both of which are abundant at the site) significantly reduces oak seedling recruitment. The role of small mammals in oak seedling mortality has been suggested by a number of studies (e.g., Adams and others 1987, Adams and others 1997, Berhardt and Swiecki 1997, Borchert and others 1989, Davis and others 1991, Griffin 1976, McCreary and Tecklin 1997). However, in cases where seedlings are protected from herbivory with the use of window screening or tree shelters, it is difficult to separate the effects of small mammals from insects, since these treatments exclude both. The present study indicates that small mammals play a major role in limiting recruitment of valley and coast live oak.

Finally, although there appears to be no difference in initial seedling emergence in large grazed vs. ungrazed plots, our results suggest that there may be higher mortality in ungrazed plots. These latter plots, which have been ungrazed since January 1995, now have dense herbaceous vegetation. It is possible that this thick cover of thatch and grasses either 1) negatively affected the oak seedlings directly by competing for water (Gordon and Rice 1993), or 2) attracted higher densities of herbivores. We believe that the higher mortality was due to the latter, in particular herbivory by insects. This past summer (2001) we observed an outbreak of grasshoppers at our site, and many of our seedlings, in all treatments, were defoliated. Previous studies have found that reducing cover of grasses, either by weeding or grazing, significantly enhanced emergence or survivorship in oaks (Adams and others 1997, Berhardt and Swiecki 1997, McCreary and Tecklin 1997). While reduced competition was one outcome of these treatments, several studies note that weed control also reduced damage by animals that are attracted to thick herbaceous cover, such as voles (Bernhardt and Swiecki 1997) and grasshoppers (McCreary and Tecklin 1994).

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a) For purposes of this section, "oak" means a native tree species in the genus Quercus, not designated as Group A or Group B commercial species pursuant to regulations adopted by the State Board of Forestry and Fire Protection pursuant to Section 4526, and that is 5 inches or more in diameter at breast height.

(b) As part of the determination made pursuant to Section 21080.1, a county shall determine whether a project within its jurisdiction may result in a conversion of oak woodlands that will have a significant effect on the environment. If a county determines that there may be a significant effect to oak woodlands, the county shall require one or more of the following oak woodlands mitigation alternatives to mitigate the significant effect of the conversion of oak woodlands:

(1) Conserve oak woodlands, through the use of conservation easements.

(2) (A) Plant an appropriate number of trees, including maintaining plantings and replacing dead or diseased trees.

(B) The requirement to maintain trees pursuant to this paragraph terminates seven years after the trees are planted.

(C) Mitigation pursuant to this paragraph shall not fulfill more than one-half of the mitigation requirement for the project.

(D) The requirements imposed pursuant to this paragraph also may be used to restore former oak woodlands.

(3) Contribute funds to the Oak Woodlands Conservation Fund, as established under subdivision (a) of Section 1363 of the Fish and Game Code, for the purpose of purchasing oak woodlands conservation easements, as specified under paragraph (1) of subdivision (d) of that section and the guidelines and criteria of the Wildlife Conservation Board. A project applicant that contributes funds under this paragraph shall not receive a grant from the Oak Woodlands Conservation Fund as part of the mitigation for the project.

(4) Other mitigation measures developed by the county.

(c) Notwithstanding subdivision (d) of Section 1363 of the Fish and Game Code, a county may use a grant awarded pursuant to the Oak Woodlands Conservation Act (Article 3.5 (commencing with Section 1360) of Chapter 4 of Division 2 of the Fish and Game Code) to prepare an oak conservation element for a general plan, an oak protection ordinance, or an oak woodlands management plan, or amendments thereto, that meets the requirements of this section.

(d) The following are exempt from this section:

(1) Projects undertaken pursuant to an approved Natural Community Conservation Plan or approved subarea plan within an approved Natural Community Conservation Plan that includes oaks as a covered species or that conserves oak habitat through natural community conservation preserve designation and implementation and mitigation measures that are consistent with this section.

(2) Affordable housing projects for lower income households, as defined pursuant to Section 50079.5 of the Health and Safety Code, that are located within an urbanized area, or within a sphere of influence as defined pursuant to Section 56076 of the Government Code.

(3) Conversion of oak woodlands on agricultural land that includes land that is used to produce or process plant and animal products for commercial purposes.

(4) Projects undertaken pursuant to Section 21080.5 of the Public Resources Code.

(e) (1) A lead agency that adopts, and a project that incorporates, one or more of the measures specified in this section to mitigate the significant effects to oaks and oak woodlands shall be deemed to be in compliance with this division only as it applies to effects on oaks and oak woodlands.

(2) The Legislature does not intend this section to modify requirements of this division, other than with regard to effects on oaks and oak woodlands.

(f) This section does not preclude the application of Section 21081 to a project.

(g) This section, and the regulations adopted pursuant to this section, shall not be construed as a limitation on the power of a public agency to comply with this division or any other provision of law.

Restoring oak woodlands in California: theory and practiceRestoring Oak Woodlands in California: Theory and Practice

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Ecological importance of California oak woodlands

Vegetation types dominated by oak trees cover about 4 million hectares in California (Bolsinger 1988), or roughly 10% of the state’s land area. These extensive oak woodlands serve a number of important ecological functions. Oak woodlands play a critical role in protecting soils from erosion and landsliding, regulating water flow in watersheds, and maintaining water quality in streams and rivers. Oak woodlands also have higher levels of biodiversity than virtually any other terrestrial ecosystem in California. At least 300 terrestrial vertebrate species (Block, Morrison, and Verner 1990), 1,100 native vascular plant species (CalFlora Database 1998), 370 fungal species and an estimated 5,000 arthropod species (Swiecki et al. 1997a) are associated with California oak woodlands.

More than twenty-five oak species, natural hybrids, and varieties are native to California. California oaks also occur as components in desert plant communities and conifer-dominated montane and forest ecosystems. In this chapter, our discussion is limited to the low elevation oak woodlands of valleys and foothills. In these regions, almost all precipitation falls between September and May and seasonal totals vary from about 27 cm in the driest woodlands to 93 cm or more in the more mesic areas. Winter temperatures only occasionally drop to or below freezing. Summer temperatures are moderate near the coast, but most inland areas are subject to intermittent summer temperatures above 38 C. The dominant oaks in these areas are valley oak (Quercus lobata), blue oak (Q. douglasii), interior live oak (Q. wislizeni) and coast live oak (Q. agrifolia). Engelmann oak (Q. engelmannii) replaces blue oak in southern California.

Loss of oak woodlands

California’s oak woodlands have been dramatically reduced in extent over the past 230 years. European and later American settlers greatly reduced woodland cover, most dramatically in the first 50 years after the discovery of gold in

California in 1848. Several oak species were extensively harvested for fuelwood and charcoal production, but most California oaks had little or no commercial value as timber. Widespread destruction of oak woodlands to clear land for more profitable uses has been an accepted practice which continues to the present day in many areas. Clearing for intensive agriculture, rangeland "improvement", and urban development have eliminated oak woodlands from much of their former range.
Stringers of oaks along creeks and occasional oaks scattered in agricultural fields and on grassy hillsides sometimes provide the only hints of the extent of former woodlands.
Biotic and physical characteristics of former and extant woodlands have also been changed from their presettlement condition. Numerous plant and animal species have been irrevocably lost, while many nonindigenous plant and animal species have become so widespread that their eradication is impossible. Although many native species are still present in these degraded ecosystems, the herbaceous layer has become dominated by nonindigenous annual grasses and forbs.
Grazing and clearing have increased soil compaction and erosion. In some areas, hydraulic mining removed entire hills and redeposited their contents downstream.
Dams have flooded tens of thousands of hectares of oak woodland and have changed historic water tables and flooding regimes under which riparian oak forests developed. Groundwater pumping and accelerated streambed incision have also lowered water tables in valleys.
Although all oak woodland types have been affected by the changes brought about by European settlement, woodlands dominated by blue, valley, and Engelmann oak have been the most adversely affected. For all of these species, losses due to clearing for agriculture, urbanization, and fuelwood have been compounded by regeneration failure within existing stands. Sapling populations in many oak woodlands are insufficient to offset mortality and maintain current stand densities (Bolsinger 1988, Swiecki et al. 1997c). Without natural regeneration, woodlands have gradually thinned to open oak savannas, which in turn are

converted to grasslands dominated by nonindigenous annuals. Studies of the age structure of various oak stands indicate that most existing woodlands are composed primarily of second growth that established between the 1850s and the first decades of the twentieth century (e.g., Mensing 1992). Widespread suppression of oak regeneration, especially in blue oak woodlands, is a relatively recent phenomenon that is largely restricted to lands that have been used for livestock range for many years (Swiecki and Bernhardt 1998).

The need for oak woodland restoration is a consequence of past and current management practices that have degraded or destroyed these ecosystems. Thus, restoration and management of oak woodlands are inseparably linked. For either oak woodland restoration or sustainable management of existing woodlands, we must answer the following questions:

- What do you have? What is the condition of the existing ecosystem and how did it come to its current state?
- What do you want? What outcomes for the ecosystem are both attainable and ecologically appropriate?
- How do you get what you want? What inputs and techniques can be applied to achieve restoration / management goals?
- Are you getting what you want? How do we assess the success of restoration / management efforts?

In this paper, we will consider the theoretical basis for addressing these four questions. We will also discuss practical applications of the principles that follow from these theoretical considerations.

What do you have? - Past and present vegetation and management

Restoration logically begins with an understanding of the condition of the resource and the management history that has brought it to its current state.

1. What is the current composition of the vegetation? Current vegetation is the starting material of a restoration project and may include desirable species to be favored as well as undesirable species to be suppressed or eradicated.
2. What was the nature of the former woodlands? Historical photos, accounts, and herbarium specimens can be used to gain insight into the former character of the woodlands, but it is impossible to definitively reconstruct the presettlement oak woodland vegetation. Nonindigenous plants introduced by the earliest

European explorers and early Spanish colonists had become widespread before the 1850s, and much of the original oak woodland canopy was cut or burned off by the 1890s. For most California oak woodlands, the earliest aerial photography dates to the 1930s and very little ground-level photography was taken before the 1880s. Thus, the photographic record begins after major changes were completed. Earlier written accounts can add some information, but specific details on the floristic composition of oak woodlands are rare.

3. How have management practices and other human activities shaped current site conditions? Although information gaps will typically exist, historical site analysis can reveal important details about the succession of human impacts that have shaped the current landscape. Because site specific historical data is difficult to obtain, it is often necessary to rely on more regional historical information. However, the history of land ownership and management for many parcels is so complex that one should generally not assume that past management has been uniform across wide areas.

The analysis of past and current vegetation and management can help one determine what outcomes are possible for a site, and what inputs may be necessary to achieve these outcomes. A key question to be addressed in this analysis is whether a site can still support the type of woodlands that were historically present. For example, valley oak is found where its roots access relatively shallow water tables or exploit a large reservoir of available capillary water stored in the soil profile. In historic valley oak sites where precipitation and soil available water holding capacity are low, significant lowering or elimination of shallow water tables may render the site unsuitable for this species.

What do you want?

Goals for oak woodland restoration

The overall goal of ecological restoration is to return an ecosystem to a former condition that includes the entire complement of plants and animals and the dynamic processes found in the naturally-occurring state. Presettlement conditions are the benchmark for the natural state, but we cannot define these conditions with certainty. While we remain unsure about the natural condition of the oak woodlands and the processes that maintained them, we can be fairly certain that restoring these woodlands to the presettlement state is virtually impossible. Thus, the goals we set for oak woodland restoration and management must be more modest than the goal of complete ecological restoration. The following goals are attainable because they acknowledge limitations due to the current degree of ecological degradation and our lack of knowledge about the pristine ecosystem.

1. Reestablish appropriate oak species in areas that did or could have supported oak woodlands previously and are now capable of supporting this vegetation type.
2. Establish sustainable populations of historically known and likely indigenous plant species and associations within oak woodlands.
3. Manage remnant oak woodlands and restored stands to permit natural regeneration and maximize the cover and dominance of indigenous plant species while minimizing the cover of nonindigenous species.
4. Promote reestablishment of natural biotic systems, including interacting microbial, invertebrate, and vertebrate communities, within restored woodlands.

Ultimately, all four goals should be met in a successful restoration. However, it may not be possible to effectively address all goals in the initial phase of a restoration project. Because oaks provide structure and canopy influence that drives both vegetation and wildlife dynamics in oak woodland ecosystems, establishing oak canopy is usually the initial goal addressed in a restoration project.

Prioritizing restoration sites

Although the need for oak woodland restoration is great, financial resources available for undertaking oak woodland restoration will always be limited. To make the best use of limited resources, it is desirable to compare the costs and benefits of potential project locations and technical approaches. Such an analysis would ideally be done on a regional basis, but issues of land ownership, land use, and sources of funds immediately pose constraints that restrict site consideration. Consequently, prioritization is typically conducted among lands under a common ownership (e.g., by a public park district) and on

individual parcels.
Potential restoration sites can be prioritized according to existing oak resources, site quality, project benefits, and long-term sustainability. These criteria take into account the relationship of the restored area to the landscape in which it exists, and how it will influence or be influenced by existing oak woodlands in the area.

1. Presence of oaks on the site and proximity to existing woodlands. Existing woodlands and oaks in and near restoration sites are a likely source of locally-adapted plant germplasm as well as a potential reservoir of other organisms endemic to oak woodlands. Seeds and other propagules of understory plants from adjacent oak woodlands can be transported to restoration sites through the action of animal vectors, wind, and water. The passive movement of native nonvascular plants, lichens, fungi, actinomycetes, and bacteria into the restoration site is also favored if oak woodlands adjoin the restoration site.
2. Site quality. Site quality is the ability of a site to support oak establishment and growth. Site quality is primarily related to physical factors such as soils, climate, hydrology, and topographic position. However, oak survival and growth are also constrained by competing vegetation, herbivores, and disturbance factors that affect overall site quality for restoration purposes. Faster establishment of oak woodlands can be achieved by focusing initial restoration efforts on high quality sites. Furthermore, restoration costs are normally lower per unit area on high quality sites than on low quality sites.
3. Site-specific benefits. Ecological, societal, and economic benefits provided by oak woodland restoration can vary greatly between sites. Depending on soil type and topography, benefits such as erosion protection and soil stabilization may be significant or not. Restoration projects near migration corridors or critical habitat for species of special concern may provide greater benefits for wildlife habitat. Restored woodlands near urban areas may provide more direct benefits to human populations (recreation, modification of urban climates, hydrologic effects) than woodlands in remote areas.
4. Likelihood of long-term sustainability. Restored woodlands that will require

few or no additional inputs after the original project will typically provide maximum benefits for minimum cost. Overall, prospects for sustainability result from a combination of site qualities (e.g., existing populations of understory plants), management (e.g., grazing practices), and land ownership and use that confer a degree of long-term stability (e.g. natural reserves or park lands).

Reserves owned by public agencies or private land conservation organizations may ensure long-term protection against changes in land use, but projects on these lands may not be self-sustaining over the long term if management practices are poor or site quality is marginal.

How do you get what you want?

Factors that constrain regeneration

Oak woodland restoration is necessary where natural regeneration has failed in the past or is currently failing. The first task in planning a restoration project is a site analysis to determine what factors are constraining natural regeneration of oaks and associated plants. Suitable sites for restoration are those in which site management has inhibited oak woodland regeneration but edaphic and climate factors are not critically limiting for seedling establishment.

The influence of management on oak reproduction is illustrated by the fact that oak seedlings volunteer readily in horticultural landscapes and along roadsides beyond pasture fences. These environments constitute safe sites for oak reproduction. Many of the numerous differences that exist between adjacent garden and rangeland environments are directly related to the ease with which oak seedlings establish in the former environment but not the latter. Differences in acorn dispersal, seedbed conditions, herbivory, soil moisture, shading, and fire frequency influence seedling establishment. As discussed below, one or more of these factors may critically constrain natural regeneration at a restoration site.

Acorn dispersal

Most acorns that fall land under or near maternal tree canopy. If seedbed conditions are favorable, some of the acorns that are not eaten or carried off by animals will germinate and become part of a persistent seedling bank. In blue oak (Swiecki and Bernhardt 1998) and probably other California oaks, this seeding advance regeneration is suppressed by overstory trees. Although such seedlings can persist many years in the understory, they are not recruited to sapling or tree size classes unless overstory competition is reduced though decline, mortality, or removal of the oak overstory. Hence, gap-phase replacement is a primary mode of reproduction in at least some California oaks.

Establishment of oak seedlings well beyond the maternal canopy depends primarily on dispersal by animals. The California scrub jay (Aphelocoma californica) is probably the most important acorn vector due to its abundance, wide distribution, and ability to cache thousands of acorns in a season. Because scrub jays typically bury their acorns in sites with loose soil and/or a layer of organic debris, unrecovered acorns are well-positioned to germinate and develop into seedlings. Scrub jays do not randomly place acorns in grasslands, but typically cache acorns near landmarks such as fencelines, rock outcrops, trees, and shrubs. Hence, reinvasion of grasslands by oaks can be limited in part by a lack of acorns.

In riparian systems, floodwaters may also be an important means of long-distance dispersal. Dam construction has eliminated annual flooding events from most California rivers, largely eliminating flood flows as a major acorn dispersal method.

Seedbed conditions

Most California oaks do not require stratification and begin to germinate as soon as moisture is available in the autumn. However, acorns may fall several months before the onset of the winter wet season. Unless acorns are buried or protected by leaf litter, they desiccate and lose viability during the warm dry conditions typical of late summer and autumn. In nongrazed woodlands, a substantial layer of organic debris accumulates on the soil surface beneath oak canopies. Acorns falling from the canopy readily penetrate into this duff layer where they are largely protected from desiccation, overheating, and to some degree, from vertebrates. Because long-term grazing reduces or eliminates the litter layer beneath trees and compacts soils, most acorns in grazed lands remain exposed on the soil surface where they desiccate or are consumed by livestock and other vertebrates. Sudworth (1908) noted that poor seedbed conditions inhibited reproduction of several oak species in both grazed and agricultural lands.

Herbivory

Herbivory can severely limit the growth and survival of oak seedlings and saplings. Livestock, deer, and rodents all have the potential to limit or eliminate oak reproduction, but the relative importance of each herbivore varies by location. Livestock, most commonly cattle, are the most important herbivore limiting oak regeneration over the greatest proportion of California’s oak woodlands. Browsing and trampling by cattle shortens the life of individual seedlings and can deplete or eliminate understory advance regeneration. Cattle browsing can also indefinitely suppress the growth of seedlings located beyond the canopy that would otherwise recruit to sapling and tree size classes. By prolonging the period that juvenile oaks remain in small size classes, herbivory increases the susceptibility of oak regeneration to both subsequent herbivory and fire. The impact of livestock herbivory varies somewhat by species. The less palatable evergreen oaks Q. agrifolia and Q. wislizeni are less severely browsed than valley oak and blue oak.

Gophers, ground squirrels, and voles can kill juvenile oaks by chewing and girdling stems. Elimination of predators and alterations in vegetative composition and structure can increase rodent populations to the point that they can inhibit oak reproduction. Rodent populations vary spatially and can fluctuate from year to year due to habitat conditions, predators, and pathogens.

Because rodents are not problems at all locations, observations at the restoration site are needed to determine whether rodent herbivory is likely to be a significant constraint. Insects, particularly grasshoppers (Melanoplus spp.) sometimes cause significant damage to young oak seedlings, but insect herbivory is not usually a severe constraint to oak reproduction (Swiecki et al. 1991).

Soil moisture

Water stress associated with summer drought also limits oak seedling survival and growth. Water stress effects are most acute at the early seedling stage. As oak seedlings become established and develop an extensive root system, water stress is less likely to cause mortality, although it may limit growth rates and thereby prolong the period during which seedlings are susceptible to herbivores or fire. Seedling tolerance to water stress varies between oak species. Vegetation influences the level of water stress to which oak seedlings are exposed in several ways. Overstory and understory plants compete with oak seedlings for available soil moisture. Overstory and tall understory species can also shade oak seedlings, elevate relative humidity, and reduce temperature and wind speed, thereby reducing evapotranspiration demand. Many California plant ecologists accept the conjecture that soil moisture is less available in oak woodlands now than it was in presettlement times due to the replacement of native herbaceous vegetation with nonindigenous annual grasses and forbs. Definitive evidence in support of this hypothesis is lacking, largely because the nature of the presettlement understory is poorly understood. Blue oak seedlings experience high levels of water stress during the summer (Griffin 1973), but it is not possible to determine whether these levels of summer water stress have changed since settlement.

Insolation

In open woodlands and clearings, high levels of insolation (solar radiation) function mainly to increase evaporative demand and consequently, water stress. In relatively xeric sites and/or dry years, high levels of insolation can limit seedling survival in some oak species (Muick 1997, Borchert et al. 1989). In some xeric areas, the density of existing second-growth oak stands is greater on northerly aspects or is entirely restricted to north slopes, indicating that insolation has strongly affected regeneration since settlement.

Oak seedling and sapling growth and survival can also be limited by a lack of light in woodlands with closed or nearly closed canopies. Levels of shading that inhibit oak growth and survival vary by growth stage, site conditions, and oak species. Blue oak seedlings can establish under canopy, recruitment to the sapling stage typically requires a canopy opening (Swiecki et al. 1997b). Blue oak saplings that become overtopped by faster-growing species usually decline and die. Although shady conditions generally favor seedling establishment in xeric sites, shade may reduce seedling establishment if soil moisture is not limiting (Borchert et al. 1989).

Fire

Most California oaks possess one or more adaptations that allow them to tolerate infrequent fires. Mature trees of some species, including Engelmann, blue, and valley oak, tolerate light to moderate ground fires with little damage. However, more intense fires may kill trees outright or create fire scars that facilitate invasion by wood decay fungi and lead to early mortality. Virtually all young California oaks resprout readily after topkill by fire, and some species, including Q. agrifolia and Q. wislizeni, crown sprout vigorously after topkill even as mature trees.

In mesic areas where black oak (Q. kelloggii) or Oregon oak (Q. garryana) coexist with fire-sensitive conifers, infrequent fires may be important in suppressing succession to coniferous forest and maintaining oak as the dominant canopy species. However, these situations are the exception rather than the rule in California oak woodlands. In most low elevation woodlands, fire is not required for regeneration or to maintain the dominance of the oak overstory.

Even though oak seedlings and saplings resprout readily after topkill, fire causes low to moderate levels of mortality in juvenile oaks. After topkill, juveniles may require at least several years to recover their aboveground biomass (Figure 1). Repeated destruction of the shoot in successive years depletes seedling energy reserves thereby increasing the incidence of fire-related mortality and reducing sapling recruitment (Swiecki et al. 1997b).

Frequent fire suppresses oak reproduction and facilitates conversion of woodlands and savannas to grasslands, a pattern seen in other areas. The combination of repeated fire and grazing is especially effective for suppressing regeneration, and was historically used to convert woodlands to grasslands.

Figure 1. Effect of fire on survival and height growth of natural juvenile blue oaks in a grassland dominated by introduced annual grasses. Shoot heights on the

Y-axis were recorded 2 years after the fire. Points below the diagonal line represents oaks that have not regrown to their pre-fire height.

Addressing constraints with restoration inputs

At a given site, one or more of the constraining factors listed above may be inhibiting seedling establishment and growth. The minimum restoration inputs needed to restore oaks at a given site are those that address the critical site constraints, i.e., factors that completely inhibit plant establishment. Most restoration inputs have multiple effects on the ecosystem and can change the intensity of several constraints, either positively or negatively. An integrated approach is needed to balance the positive and negative influences of selected inputs in the design of a restoration project.

Each restoration input also has corresponding costs in terms of labor and materials, as well as possible ancillary costs (e.g., disposal of used materials). Although some inputs may provide statistically significant differences in survival and growth, they may not necessarily be cost effective.

To achieve a high level of cost effectiveness, not only should inputs be matched to site constraints, but the least expensive effective inputs should be selected.

Planting

Genetic considerations

Locally-collected seed is recommended for restoration plantings for two interrelated reasons. First, local genotypes are likely to be well-adapted to local soil and climate conditions, and therefore are likely to perform well. The importance of using local ecotypes to ensure seedling survival and growth is well documented for commercial conifer species, and evidence for local adaptation has been demonstrated for northern red oak (Quercus rubra) from the eastern USA (Sork et al. 1993). Secondly, plantings from non-local seed may contaminate the local gene pool by introducing maladaptive alleles into the local population. Through outcrossing with non-local individuals, specialized traits of local populations may be compromised or diluted.

Unfortunately, little is known about the genetics of California oak species. Phenotypic variability between oak populations has long been noted in California (Jepson 1910). The common occurrence of interspecific oak hybrids indicates that gene flow between species may contribute substantially to variation between local oak populations (Dodd et al. 1997). Several studies have examined the amount of phenotypic variation that exists within and between populations of in several oak species (e.g., Rice et al. 1993,1997). However, current data do not indicate how large a local seed collection zone should be, or whether oaks growing on hilly terrain differ genetically from oaks of the same species growing on adjacent valley floors.

For at least some California oak populations, we may not be able to assume that local germplasm is highly adapted to current site conditions. If site conditions are more xeric now than they were prior to settlement, oak genotypes from a more xeric location (e.g., lower elevation and/or latitude) might be better adapted to the site than the extant local population. For example, initial results from a reciprocal transplant test indicate that blue oak seedlings from a distant xeric site (Sierra Nevada foothills) performed better than the local germplasm at a relatively mesic site (North Coast range) (Rice et al. 1997).

Defining local seed is further complicated by the movement of oak germplasm between distant populations by humans. Along aboriginal routes of migration and trade, human-assisted gene flow may have significantly affected population genetics of oaks and other species used for food. Recently, the increased horticultural use of California native oaks in urban and rural landscaping, including highway plantings, has distributed many non-local oaks amid oak woodlands. In some areas, acorns collected from local trees may not represent germplasm of a locally-adapted population.

Until further genetic studies are completed, the designation of the local seed area for each species must be guided by a knowledge of the restoration site and local woodlands. In practice, woodlands within the same watershed located within a few to perhaps 10 km of the restoration site may be considered likely candidates for local germplasm. Microclimate and soils of the source site should match the target site to the degree possible. Collections from several source areas representing as many trees as possible should be used to obtain greater levels of diversity in the germplasm. Acorns should not be collected from trees likely to be pollinated by horticultural oaks of unknown provenance. In areas where oak populations have been extirpated or reduced to a few remnant individuals, truly local germplasm may not exist or may have insufficient levels of genetic diversity. In such situations, introduction of seed from more distant areas may be necessary.

Planting stock: seed vs. transplants

Direct planting of acorns has several significant advantages over transplanting even though oak seedlings can be successfully established by either method. Unlike acorns, transplants require space for propagation and care in the nursery. Transplants are more difficult to store and transport, and require more effort and care in planting than acorns. When direct-seeded in the field, seedlings of many California oak species produce a long taproot which can extract moisture from deep in the soil profile (Matsuda et al. 1989). In both container-grown and bareroot nursery stock, the dominance of the taproot is destroyed, impairing the drought tolerance of the developing seedling. Consequently, transplants normally require some irrigation, whereas direct-seeded acorns do not. Finally, nonindigenous soil-borne pathogens or insect pests from the nursery may be introduced with the transplants into the planting site; this risk is negligible for direct-seeded acorns. For most restoration plantings, transplants have no long-term survival or growth advantages over direct seeded acorns that would offset their increased cost and other drawbacks.

The choice of planting stock also has genetic implications. Direct-seeded acorns are subjected to site-specific selection pressure at the earliest possible stage of growth. This facilitates selection for seedling characteristics that may contribute to fitness, including resistance to insects and other herbivores, drought and temperature tolerance, emergence date, the structure and growth rates of roots and shoots, and response to local mycorrhizal fungi and other rhizosphere microorganisms. Selection pressures imposed on oak seedlings grown as nursery stock are vastly different from those encountered at the restoration site and typically bear little relationship to field conditions. Hence, genotypes that are successful in the nursery may not be the same as those that would have succeeded in the field. Paradoxically, the main advantage of transplants, i.e., ensuring that every planting site contains a seedling, is a disadvantage in terms of allowing natural selection to function.

Planting practices

In addition to addressing inadequate acorn dispersal, planting ameliorates poor seedbed conditions. A suitable seedbed can be prepared by turning over and breaking up the upper 25-30 cm of the soil profile with a shovel. Augering and backfilling deep (60-90 cm) planting holes is more expensive and does not always provide a clear benefit (e.g., Figure 2), but may be beneficial where root penetration is inhibited by subsurface strata such as tillage pans or clay lenses. Deep augered holes can also settle excessively after wetting, which can be detrimental to seedling establishment.

Figure 2. Percent of valley oaks in each of 4 height classes. Oaks were planted from acorns in 1989 (Bernhardt and Swiecki 1997, west hillside). The site (3 ha) is grazed annually at varying stocking levels. The season and duration of grazing has also changed from year to year, but usually is winter-spring. Nonwoven polypropylene landscape fabric (90 cm square) covered with waste wood chips was used at mulched sites. Ten years after planting, more than half of the surviving seedlings are still less than 60 cm tall. Vaca cages to protect seedlings from cattle grazing are essential for seedling survival at this site.

Oaks are strongly mycorrhizal, although the mycorrhizal fungi associated with California oaks are poorly characterized. Soil taken from existing woodlands can serve as a source of inoculum for mycorrhizal fungi and other beneficial soil microorganisms and invertebrates. Planting acorns with as little as 250 ml of woodland soil has been shown to have beneficial effects on seedling growth (Scott and Pratini 1997). Inoculating planting sites with woodland soil might be cost effective on some sites, but may not be necessary if potential sources of inoculum are close enough to permit natural colonization.

Fertilizer is considered to be an inexpensive input, but may be unnecessary or even counterproductive. In oak woodlands, soil moisture is typically more limiting than levels of mineral nutrients in the soil (Dahlgren et al. 1997).

High levels of phosphorus can suppress mycorrhizal development, and excessive levels of nitrogen can increase susceptibility of plants to insect damage.

An organic mulch applied over the planting site moderates soil temperatures, reduces evaporative water loss, helps maintain high humidity around the seed, facilitates seedling emergence by preventing crusting of the soil surface, suppresses the growth of competing vegetation, and releases plant nutrients as it decays. Mulch containing chipped woody material may also provide a food base for woodland microorganisms that utilize woody debris. Such woody substrates are normally lacking in annual grasslands. Mulches can significantly improve early seedling growth and survival (Bernhardt and Swiecki 1997), but it is unclear whether long-term survival and growth benefits are sufficient to make this input cost effective for all sites (Table 1).

Table 1. Survival and relative costs of different sets of restoration inputs for valley oaks planted from acorns in 1989 (Bernhardt and Swiecki 1997, west hillside) and shown in Figure 2.

Treatment	Survival in 1999	Set up worker-hours per treatment	Initial (1989) material cost	Setup hours/ surviving site	Initial material cost/surviving site
No Vaca cage, no mulch	0	.23	0	-	-
Vaca cage, no mulch	57%	0.62	$5.36	1.06	$9.19
Vaca cage, mulch	67%	1.01	$6.40	1.51	$9.6
Vaca cage, mulch, auger	80%	1.14	$7.32	1.43	$9.15

Some highly effective planting techniques entail little or no cost. Seedling emergence rates can be improved by inspecting acorns at planting and discarding those with evidence of insect damage or decay. Planting several acorns per site increases the probability of having at least one successful seedling per site (Swiecki and Bernhardt 1991). Planting early, immediately after the first autumn rains, ensures that germinating acorns can take full advantage of seasonal rainfall. Shoot growth in the first two seasons after planting is greatest for acorns planted at the earliest possible date (McCreary 1990). Planting at an adequate depth (about 5 cm) protects acorns from desiccation and reduces the likelihood that they will be eaten by rodents (Tietje et al. 1991). Seedling survival and growth rates can be also improved by selecting favorable planting sites. For example, damage by rodents such as ground squirrels can be reduced by simply avoiding areas with active colonies (Bernhardt and Swiecki 1997). Soil moisture limitations can be minimized by avoiding drought-prone areas, such as slopes with southwestern aspects or shallow soils, and planting preferentially in areas with naturally high soil moisture. In one planting, we observed that growth differences associated with highly favorable soil conditions far exceeded the effects of mulching and augering (Bernhardt and Swiecki 1997). It may not be possible to identify all of the most favorable microsites or restrict planting to them, but one can make better use of limited resources by avoiding obvious problem areas.

At any site, a given set of inputs may give rise to a range of outcomes depending on the year. In projects that require oak planting, a useful hedge against temporal stochastic constraints (e.g., extended drought, accidental fire, herbivore population fluctuations) is to plant in a number of successive years. This tactic has the effect of averaging risks over time and increases the chance that favorable growing conditions will coincide with at least some plantings.

Protection from herbivores

Livestock

Whether oak woodland restoration relies on natural regeneration or planting, it cannot succeed in areas that are heavily grazed by livestock (Figure 2). Long-term livestock grazing is highly destructive to oak woodland ecosystems because its adverse effects extend far beyond herbivory and trampling of oak seedlings. Livestock deplete the acorn supply and degrade seedbed conditions by removing litter and compacting soil. Excessive livestock grazing also increases populations of many nonindigenous annuals. Some of these (e.g., yellow starthistle, Centaurea solstitialis) extract water late in the season from deep in the soil profile, increasing competition for soil moisture. Potentially negative effects on the soil microflora and invertebrate fauna from compaction and changes in the herbaceous layer are also likely but are largely undocumented.

Cessation or strict limitation of grazing may be the only restoration input necessary where livestock grazing is the primary factor suppressing oak reproduction. Reduction in grazing intensity may be accomplished by reducing the season of use, animal stocking levels, and/or grazing frequency (e.g., rest rotations with no grazing in certain years). The maximum amount of grazing that is compatible with oak woodland restoration will vary greatly by site, but mesic sites will generally tolerate higher levels of grazing pressure than xeric sites.

Without continual suppression by livestock browsing, existing seedlings in open, noncanopied positions will recruit to the tree stage, but the length of time required will vary with site quality, oak species, and plant condition. Seedlings that have been suppressed for an extended period may require at least several years to reestablish a vertical leader. Removing or severely restricting grazing can also permit the recovery of understory seedling advance regeneration under oak canopy, other suppressed indigenous plant species, and soil ecosystem processes.

Many of the most aggressive nonindigenous weeds in California oak woodlands and savannas are favored by open sites, soil disturbance, and selective removal of competing vegetation by grazing animals. In time, many of these species will decline in dominance after grazing is eliminated and an oak overstory is reestablished. However, over a shorter time horizon, undesirable changes in the herbaceous layer may develop that may require management with tightly controlled grazing, herbicides, or other techniques. In northern California, the introduced perennial Harding grass (Phalaris aquatica) is suppressed in open sites by grazing but can develop into dense, highly competitive stands if grazing is removed (Bernhardt and Swiecki 1997). The short-term response of understory vegetation to a release of grazing pressure is largely site specific, and depends on existing populations of native and nonindigenous plants, site conditions, weather patterns, and management practices.

Reduced grazing pressure can also influence wildlife populations in ways that may affect the restoration process. Ground squirrel populations tend to be higher in grazed than in ungrazed locations, so reduced grazing may reduce damage caused by this species. Where cessation of grazing leads to heavy grass cover, vole (Microtus californicus) populations may increase to levels that reduce oak seedling establishment. Although the long-term prospects for restoring the oak woodland ecosystem are vastly improved when grazing is reduced or eliminated, close monitoring and active management may be required to minimize negative changes during the transitional period.

In areas where livestock grazing cannot be eliminated or adequately restricted, it is still possible to protect individual oak seedlings or saplings from browsing by using single tree exclosures. Individual exclosures must be relatively sturdy to withstand the abuse of cattle that pull at protruding oak branches and rub against the exclosures. For the past 10 years, we have successfully used a low-cost single-plant exclosure of our own design (Vaca cage) to protect both existing oak saplings and new planting sites from cattle (Swiecki and Bernhardt 1997, Figure 3). Vaca cages have been effective in protecting individual oaks or planting sites from cattle (Table 1, Figure 2).

Periodic inspection, repair, and height adjustment is necessary to maintain the cages' effectiveness. Cages must eventually be removed to prevent girdling and scarring of oak branches by cage wires.

Figure 3. Vaca cages used to protect direct-seeded valley oaks from seasonal cattle grazing. Even though oak growth is relatively rapid at this favorable site and cattle are only present for several months each year, below browse line nearly all branches outside of the cages have been destroyed. Cage heights can be extended to help saplings grow above browse line.

Selective protection of individual planting sites is a useful interim restoration tactic that does not require changes in the existing grazing regime. However, Vaca cages are relatively expensive and time-consuming to use, and do not protect other desirable understory vegetation or other elements of the ecosystem. If a site is excessively grazed, the ecosystem will remain highly degraded even if some oak trees are established though the use of Vaca cages.

Other herbivores

As noted above, management of herbaceous vegetation can significantly affect rodent populations and damage at a restoration site. In localized areas, direct reduction of rodent populations by trapping, baiting, or other means may be practical. Alternatively, rodents can be excluded from the individual planting sites through the use of wire-mesh or aluminum screen cylinders or plastic tree shelters (McCreary and Tecklin 1997). Although the these protective devices are relatively inexpensive, substantial amounts of labor are required to install, inspect, and eventually remove the devices. Cost-effectiveness is therefore likely to be low unless rodent populations are critically limiting.

Deer browsing can stunt oak seedlings and saplings, but damage caused by deer is typically less severe than that caused by cattle (Bernhardt and Swiecki 1997).

We have successfully used inexpensive cylindrical cages made of galvanized poultry netting to protect seedlings from deer. Such cages usually do not require maintenance other than eventual removal, but would only be cost effective where deer browsing pressure is intense. Deer are classified as game animals, and management of local populations by hunting may be sufficient to reduce their impact to a tolerable level in some cases.

Minimizing moisture stress

Vegetation management

Moisture stress can be reduced by managing competing vegetation in the immediate vicinity of the oak seedling. Maintaining bare soil in a zone at least 60 cm in diameter for one or two seasons increased survival and growth of blue oak seedlings in the first 5 years after planting (McCreary and Tecklin 1997). Bare soil areas may be produced by mechanically scraping all vegetation off the soil surface (scalping), although this method is labor intensive because repeated treatments are needed. One or two properly timed applications of a nonselective foliar herbicide (e.g., glyphosate) can also be used to eliminate competing annual vegetation around an oak seedling (Tecklin et al. 1997), but the seedling must be shielded from the spray. Some soil-applied broadleaf herbicides can have negative effects on oak root growth and soil microorganisms, and should be not be used without thorough testing. Herbicide use and scalping typically result in bare, unshaded soil around the seedling which is subject to erosion and can impede percolation of rainfall into the soil. In contrast, mulch suppresses competing vegetation and reduces rainfall runoff and evaporation without increasing erosion potential.

Depending on the weedy species present at a site, it may be more efficient to manage herbaceous vegetation across the entire restoration site. Possible management choices include properly timed mowing, tillage, or herbicide applications. Such techniques are more likely to be feasible on sites with few existing desirable plant species and where negative environmental consequences are unlikely. Regular spacing of oaks in rows or grids has been used to facilitate mowing operations in some projects. Precisely-managed, limited duration grazing can be used to differentially remove palatable herbaceous species, but unless individual oak seedlings are protected, it is difficult to manage grazing so that the reduction in herbaceous competition outweighs herbivory. Grazing around protected seedlings can lead to higher growth and survival compared to adjacent nongrazed sites (Bernhardt and Swiecki 1997).

The practical use of fire for vegetation management in oak woodlands is restricted to situations in which competing vegetation is slower-growing and/or significantly more fire-sensitive than oak seedlings and saplings. Infrequent fires (e.g., 10-20 year intervals) may be useful in suppressing the encroachment of fire-sensitive conifers into certain mesic oak woodlands (Fritzke 1997, Hastings et al. 1997). However, the frequent fires needed to manage undesirable annuals would destroy oak regeneration and inhibit oak woodland restoration. In areas that burn frequently, oak regeneration can be favored by reducing fire frequency.

Different vegetation management approaches can vary widely in cost-effectiveness. Unless competing vegetation critically limits oak reproduction, it may be more cost efficient to forego vegetation management and accept low growth rates. Such an approach is more feasible where risks associated with herbivory and fire frequency are low.

Microclimate modifying devices

Plastic tree shelters not only protect oak seedlings from rodent herbivory, but also provide a seedling microclimate characterized by reduced light intensity and air flow and increased temperature, humidity, and carbon dioxide levels (Burger et al. 1992, Minter et al 1992). The tree shelter microenvironment has profound effects on seedling morphology, especially when relatively tall (>60 cm) tree shelters are used. Stem height growth is typically enhanced in tree shelters, but shoot growth responses vary between and within species (Plumb and DeLasaux 1997, McCreary and Tecklin 1997, Burger et al. 1997). Tree shelters reduce total plant biomass and the root:shoot ratio in at least some oak species (Burger et al. 1997), which could compromise long-term survival in some situations. Tree shelters have improved initial oak seedling survival in some, but not all studies (McCreary and Tecklin 1997, Plumb and DeLasaux 1997). Both shade and protection against rodent herbivory can contribute to seedling survival, so it is difficult to determine which effect predominates when tree shelters are used. Long-term results from restoration plantings are needed to accurately evaluate the costs and benefits of tree shelters.

Aluminum screen cages also provide a modified microenvironment, though less extreme than that within plastic tree shelters. Screen cages reduce incident sunlight by about half (Adams et al. 1991) and may slightly increase relative humidity in the immediate vicinity of the seedling by reducing wind velocity. Depending on their construction, screen cages can also provide protection against rodent herbivory, at least while seedlings are small. McCreary and Tecklin (1997) found that screen cages provided less protection against rodents and less of an enhancement of shoot growth than tree shelters, whereas Costello et al. (1996) found tree shelters and screen cages to be equally effective in enhancing shoot growth and survival.

Irrigation

Although irrigation can enhance oak seeding growth, it is a relatively expensive and high-maintenance input,, especially in plantings without nearby water sources. Hand watering is labor intensive and may be inefficient due to losses from evaporation and runoff. Drip irrigation systems allow better percolation of water into the soil profile but have higher equipment costs, especially if the water source requires extensive filtration. Labor required to install and maintain a drip irrigation system can also be high. We have observed sites where oaks became highly water-stressed when irrigation was discontinued, presumably due to effects of irrigation on root distribution and/or root:shoot ratios. Irrigated planting sites are also more likely to be attacked by ground squirrels and gophers than nonirrigated sites. Consequently, summer irrigation does not always improve oak seedling growth and survival and even early benefits of irrigation can be short lived (Swiecki and Bernhardt 1997). Hence, irrigation can be one of the least cost-effective inputs in a restoration project.

Protecting existing oak reproduction

Although most oak woodland restoration projects involve planting, planting is not always necessary to restore oak canopy. In high-quality sites adjacent to oak stands, suppressed natural seedlings and saplings may be present in the area targeted for restoration. If suppression of juvenile oaks is not due to competition with the tree canopy but is associated with livestock browsing, mowing, or frequent fire, shoot protection can allow these oaks to recruit to the overstory. Suppressed juvenile oaks typically have well-established root systems, and can exhibit high shoot growth rates once they are protected. Oaks may be protected individually (e.g., with Vaca cages) or across the entire site (e.g., by eliminating grazing). Growth rates of protected juvenile oaks vary by species and with site conditions, but a minimum of 5 to 10 years of protection is typically needed to recruit juvenile oaks to a size class for which further protection is unnecessary. By protecting existing juvenile oaks, one can restore oak canopy with locally-adapted material in a shorter time than is possible by planting.

Other species

Many plant species other than oaks are important components of oak woodlands. Some other tree species, such as California buckeye (Aesculus californica), can be direct-seeded in a manner similar to oaks and can easily be included in the initial phases of restoration. Other species that are good candidates for early phases of restoration are those that do well in open sites but will not compete excessively with oak seedlings. Perennials that can be propagated by root, corm, or bulb divisions but reproduce sparingly by seed should also receive priority for reintroduction, especially in situations where local populations may be threatened with extinction. Transplanting divisions from local perennial populations can help reintroduce associated soil microorganisms and invertebrates into the restoration site. Because little is known about the genetics of other oak woodland canopy and understory species, a conservative approach toward utilizing local material is warranted.

Are you getting what you want?

Even with proper planning, factors that influence the success of restoration efforts can vary widely across space and time, and many of these factors are beyond the control of the restorationist. Outcomes for a given set of restoration inputs may vary by year, location, and species. Because our ability to predict project outcomes is limited, every restoration project is experimental. Replicated trials of specific techniques and appropriate monitoring of restoration projects over an extended time period are needed to determine whether inputs have been effective over the long term. If labor and materials costs are carefully tracked, it is also possible to determine which inputs are cost effective. This empirical data can be used to adjust inputs at the restoration site and can be used to help design future projects.

Slow oak growth rates are typical in many California oak woodlands and savannas. In nonirrigated valley oak restoration plantings protected from cattle browsing, we have observed average shoot height increases of 5 to 10 cm per year or less in upland sites of moderate quality over the first 5 to 10 years after planting. For a fast-growing species like valley oak on a favorable site, a sizeable canopy tree can develop in about 25 to 30 years. For blue oak, a slower-growing species that typically occurs in relatively xeric sites, 100 years may be required to produce a tree with a moderate canopy. With the exception of some riparian floodplains that have been removed from agricultural use, most land available for restoration is of relatively low site quality. Restoring oak canopy and understory vegetation, along with functioning natural regeneration processes, will clearly take a long time. Long-term monitoring is necessary to evaluate the success of oak woodland restoration, but few restoration projects are more than 10 years old, and few of these have been monitored beyond 3 to 5 years.

Many mandated oak restoration projects have a horticultural bias, and high initial survival rates are considered to be evidence of success. These projects often use relatively large nursery stock and maximize restoration inputs in an attempt to reduce all possible constraints to the point of insignificance. This tactic may not be cost-effective, because restoration can succeed without addressing constraints that only partially reduce growth or survival. Furthermore, the horticultural approach can eliminate natural selection for seedling characteristics that confer fitness. If seedlings vary genetically and we allow natural selection to function in the restoration process, high rates of seedling mortality can be expected in a successful restoration. If our primary restoration goal is to establish self-sustaining woodlands, it may be unwise to thwart selection for adaptive seedling characteristics through the excessive use of horticultural inputs.

Conclusions

Oak woodland restoration is in its infancy in California. Most restoration projects undertaken to date have been limited to the establishment of oak trees.

Growing California oaks is not a technically difficult task in a controlled situation, but most areas in need of restoration are not subject to tight control. Furthermore, growing a few oaks can be a relatively easy task, but establishing thousands of oaks over large areas is an arduous undertaking.

Restoration of the oak canopy can be considered successful once a naturally-regenerating stand is established, which may require a century or more. Although oaks are the dominant and most important element of oak woodlands, we cannot consider oak woodland ecosystems to be restored if other important vegetation and wildlife components are lacking. Oak woodland restoration may begin by planting oaks, but must eventually address the sustainable management of the entire ecosystem.

Current management practices, especially grazing, must be addressed throughout oak woodlands if large scale restoration of the ecosystem is to occur. By using a more holistic restoration prioritization and planning process, restoration efforts can be focused in areas where needs are high and costs can be minimized by working with natural processes. Further cost efficiency can be achieved by matching inputs to the site as closely as possible and avoiding unnecessary inputs. Restoration and management are not deterministic processes, but are influenced strongly by stochastic events and processes. Long-term monitoring of the ecosystem is needed to determine the outcome of restoration and management inputs and to provide the data needed to adjust inputs appropriately.

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